THE FLOATING HARBOUR TRANSHIPPER: WELL DOCK HYDRODYNAMICS OF A NOVEL TRANSHIPMENT CONCEPT

By

Nicholas Thomas Maxwell Johnson, BE(NavArch)(Hons), BE(MarOffEng)(Hons)

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i Declarations

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Declaration of Funding and Candidates Interests

This thesis discusses part of a larger research project that was funded by an Australian Research Council supported linkage project between Sea Transport Corporation and the University of Tasmania. As part of the linkage project the candidate was embedded within Sea Transport Corporation for a short period during the first year of candidature to become familiar with the Floating Harbour Transhipper concept. The candidate has no further link with Sea Transport Corporation beyond those disclosed here.

ii Acknowledgements

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iii Abstract

The floating harbour transhipper (FHT) concept has been developed as an alternative to traditional (side-by-side) transhipping. This concept employs a well dock at the aft end of a storage mothership in order to provide a sheltered environment for the feeder vessel, thus increasing the operational weather window. The inclusion of materials handling equipment onboard the mothership can reduce loading times to a fraction of that of traditional transhippers and the negative pressure enclosure contains dust and spillage of bulk goods. The FHT concept provides a number of advantages, particularly in terms of wider weather windows, faster materials transfer and reduced environmental impacts. These translate to increased financial viability for smaller and more remote exporters (and importers) and long term sustainability in applications previously deemed ill advised.

The well dock introduces some complex confined water effects that must be understood to unlock the full capabilities of the FHT concept. The feeder vessels entering the well dock represents a significant blockage and displaces a very large proportion of the water within the well dock. As the feeder vessel enters this constricted space it is expected to generate significant flow velocities and strong confined water effects. It was proposed that including vents within the design of the well dock could mitigate such unfavourable effects. The adoption of well docks in commercial transhipment is previously unprecedented, particularly in cases where a high blockage coefficient combines with a finite channel length and an incident sea state. Understanding the hydrodynamic influences on the feeder vessel during transhipment operations is the focus of this research project.

For this first serious investigation into the concept, an experimental campaign was undertaken using scale models to explore two scenarios that are crucial to the success of the FHT concept; the seakeeping performance of the feeder vessel when it is docked; and the performance of the feeder vessel during docking and departure manoeuvres. In order to confirm the viability of the FHT concept, the docked seakeeping performance needs to confirm that material transfer is possible in larger sea states than conventional side-by-side transhipment. For the docking and departure manoeuvres, the controllability is a key consideration and contact between the vessels is of concern across all operations. In addition to conventional resistance measurements to assess the varying loads experienced, two dimensional particle image velocimetry was also employed to analyse the flow field while the feeder vessel enters and departs the well dock.

Significantly better seakeeping performance was observed when the feeder vessel is docked within the well dock than when the same vessel operates in an open seaway. The well dock also has a significant effect on the manoeuvring performance with increased longitudinal force on the feeder vessel being observed when operating within the confined well dock. Trapped fluid at the enclosed end of the well dock caused interesting confined water effects during docking and amplified the effect when departing. Vents at the enclosed end of the well dock were proposed to reduce the confined water effects. The vents successfully reduced the adverse well dock effects with longitudinal force reducing with increased vent area. When exposed to a seaway, increased vent opening area led to more wave energy in the well dock and increased

feeder vessel motion. The relative motion between the feeder vessel keel and the well dock floor was less favourable as well dock vent size increased.

The inclusion of vents is quantified for both the seakeeping behaviour and the docking/departure performance. The use of vents is very beneficial when a feeder vessel docks or departs the well dock, however adverse effects on feeder vessel motions when docked and exposed to a seaway highlight the need for compromise. The optimum solution that covers all operational conditions likely requires the inclusion of relatively small vents. This project revealed that the challenges posed by this novel concept can be overcome through careful well dock design, confirming the FHT concept to be a viable alternative to traditional transhipping methods.

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vii Nomenclature

Symbol	Description	Units
C_{Fx}	Calibration factor – Feeder vessel force	N/V
$F_{ND\text{-}x}$	Non-dimensional longitudinal force on feeder vessel	-
F_x	Longitudinal force on feeder vessel	N
k	Wave number = $2\pi/L_w$	m^{-1}
L	Length between perpendiculars	m
L_w	Wavelength	m
t	Trim between perpendiculars	m
t_{ND}	Non-dimensional trim between perpendiculars	-
u_{CWP}	Uncertainty within the calibration factor of the wave probe	mm/V
UKC_S	Static under keel clearance	m
u_{VWP}	Uncertainty within the voltage measurement of the wave probe	V
u_{zFHT}	Uncertainty within heave measurement of the FHT	m
$u_{zND\text{-}FHT}$	Uncertainty within non-dimensional heave of the FHT	-
v	Feeder vessel speed	m/s
V_{Fx}	Voltage output – Feeder vessel force	V
z	Heave amplitude	m
z_{aft}	Sinkage at the aft post	m
z_{fwd}	Sinkage at the forward post	m
z_{LCB}	Sinkage at the LCB	m
z_{ND}	Non-dimensional heave amplitude	-
$z_{ND\text{-}LCB}$	Non-dimensional sinkage at the LCB	-
$\Delta x_{between\ posts}$	Longitudinal distance between tow posts	m
$\Delta x_{fwd\ post\ to\ LCB}$	Longitudinal distance between forward post and LCB	m
ζ_A	Wave amplitude	m
θ	Pitch amplitude	$radians$
θ_{ND}	Non-dimensional pitch amplitude	-
ρ	Water density	kg/m^3

viii Abbreviations

Abbreviation	Description
2D	Two dimensional
3D	Three dimensional
AJM	Australian Journal of Mining
AMC	Australian Maritime College
CBU	Continuous barge unloader
CFD	Computational fluid dynamics
DOF	Degree of freedom
FHT	Floating harbour transhipper
FLNG	Floating liquefied natural gas
ITTC	International towing tank conference
LCB	Longitudinal centre of buoyancy
LCF	Longitudinal centre of flotation
LCG	Longitudinal centre of gravity
LHD	Landing helicopter dock
LNG	Liquefied natural gas
LOA	Length overall
LVDT	Linear variable differential transducer
MARIN	Maritime research institute Netherlands
OGV	Ocean going vessel
PIV	Particle image velocimetry
RANS	Reynolds-averaged Navier-Stokes
RAO	Response amplitude operator
RAS	Replenishment at sea
sCMOS	Scientific complementary metal-oxide-semiconductor
SPH	Smoothed particle hydrodynamics
TML	Transportable moisture level
UKC	Under keel clearance
VCG	Vertical centre of gravity

CHAPTER 1

Thesis Introduction

1.1 Exporting bulk goods

When a company is exporting a product by bulk carrier then a balance must be struck between the cost of production plus the cost of export and the market price of the goods. In the modern-day market place there is very little that the supplier can do to influence the market price of the goods as this will often fluctuate due to supply and demand. There is also a limit where it is no longer feasible to reduce the cost of production further. This only leaves the reduction of export costs that could potentially be reduced using alternative transportation methods or negotiation with transport providers.

Given the boom and subsequent downturn in the Australian mining industry, a mining application is topical and shall be used for the purposes of this introduction. Large mines normally export large volumes, are located in geographic locations that make exporting straight forward or produce high value product to offset transportation costs. These factors often combine to allow these mines to reach and maintain their large size. The balancing act is much finer for small and medium sized mines that have more limited life (typically 5 to 15 years). These mines may be feasible to start up and begin to grow during boom times due to high market prices but as the market price falls so does the viability of the mine. A downturn in market price also leads to new mines not passing feasibility studies. Small to medium mines are often located further afield from large deep-water ports requiring additional links in the logistics chain to get their product to market leading to increased cost.

One of the biggest challenges faced for major bulk commodities is getting the product to market in an economic manner. This was a relatively easy task when ocean going vessels (OGV) were able to enter a large number of ports and most producers had a port nearby. As larger quantities of product began to be exported on larger vessels the ports required to support these vessels expanded and the number available reduced due to geographical and economic reasons. This reduction in the number of ports capable of supporting large bulk vessels left exporters with limited options. One option is to transport the product by road, train or pipeline to a deep water port for loading onto the OGV. Another option is to develop a deep water port near the production facility either by means of dredging or constructing a jetty long enough to access sufficient water depths (often extending many kilometres, such as at Cape Lambert, Western Australia). Both of these solutions are expensive in terms of capital and operating costs, often prohibitively so for all but the largest producers. Ultimately the export cost of the product is a large factor in determining the feasibility of a small to medium sized mine. When product prices fall these mines are often forced to run at a loss, stockpile goods or shut down until the market price improves.

1.1.1 Traditional transhipment

Transhipment is a potential solution for exporters that have access to a smaller port where a smaller vessel or barge can be loaded. This is the process whereby the product is transported (transhipped) from a much shallower port facility to the large OGV by a smaller (shallower draught) vessel while the larger vessel is moored offshore in sufficient water depth. The small vessel or barge (normally referred to as a feeder or shuttle) makes many trips back and forth between the shore facility and the large vessel transferring the product. It is not unusual to adopt multiple feeder vessels to decrease loading times. Transhipment has been employed for hundreds of years and as the types and volume of products have evolved so has the transhipment process to remain a proven and effective means for getting product to market. Transhipment is often more economical than using long stretches of road or rail transport to access a deep water port but is subject to a number of limitations making the export cost per tonne higher than deep water port facilities or large jetties (when readily accessible).

The transit distance required from the feeder vessel also plays a significant part in determining the effectiveness of a transhipment solution. The transit distance is mostly location dependent because the required water depth is a parameter of the OGV and the distance from shore is then defined by the local bathymetry. The water depth requirements often lead to traditional transhipment occurring at mooring locations exposed to a seaway. A further option that enables a degree of control over the mooring location is the creation of a small purpose built port for loading the feeder vessel. The requirements for such a port are generally minimal and it has the potential to improve the weather window by enabling the OGV to be moored in a more sheltered location. One example of this being applied to other transhipment alternatives to increase the weather window is Lucky Bay, South Australia, where a new harbour was formed to provide a common user export facility (Sea Transport Solutions, 2016).

There are a number of discharge options that are used in transhipping operations. The most common dry bulk transhipment processes today are either using grabs that are mounted on the OGV or a self-discharging feeder vessel. Both of these options require the feeder vessel to berth alongside the OGV in a side-by-side arrangement where the feeder vessel is exposed to the seaway. Self-discharging transhippers often require the feeder vessel to be designed around complicated materials handling equipment. Side-by-side transhipment using grabs require vessels to be cheap and easy to repair due to stevedoring damage that is common when employing grab unloading. The side-by-side arrangement using the OGVs grabs for material transfer is shown in Figure 1.1 and a tug is seen manoeuvring the left hand barge into position.

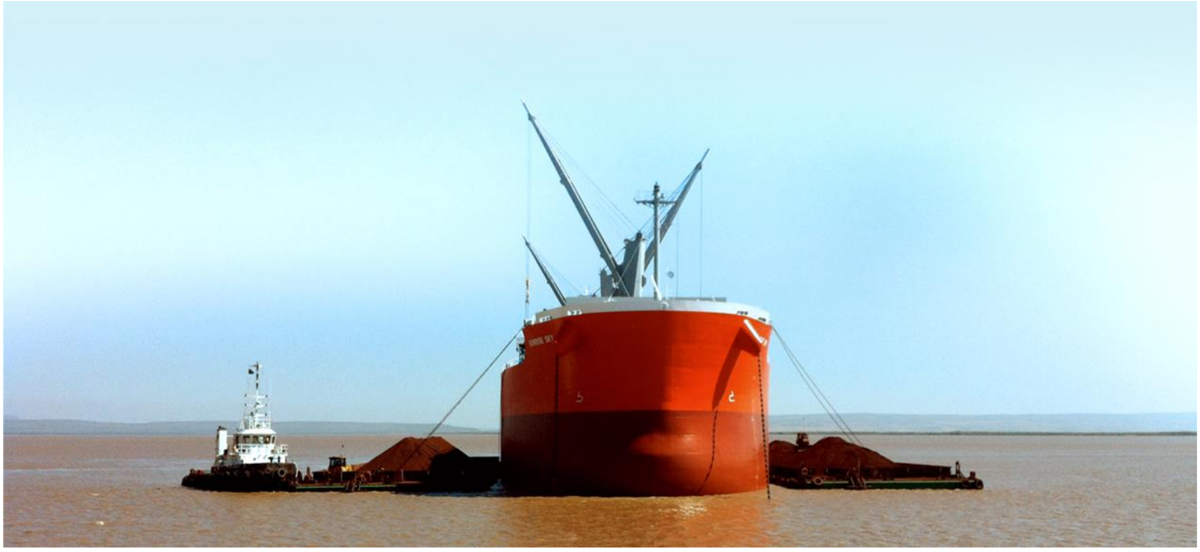

Figure 1.1: Photograph depicting transhipment operations where an unpowered barge is used as the feeder vessel and the OGV's material handling equipment is used for transfer (Transhipment Services Australia, 2018).

Traditional transhipping has several disadvantages compared to long jetties with conveyer belts; the introduction of a feeder vessel causes increased operating costs, the material transfer rate is slower and the relative motions between the feeder vessel and OGV in exposed environments leads to limited weather windows. Increased operating cost is often balanced against the decreased capital costs and the slower transfer rate can be mitigated to a certain extent. The limited weather window has the most significant impact on transhipment operations and restricts the ability to plan for slower transfer rates. Traditional transhipment processes are generally restricted to significant wave heights of 2.5 m for dry bulk cargo and 3.0 m for liquid bulk (approximately 25 knots of wind) (Ballantyne, et al., 2012, Foley, 2011). If these restrictions were applied on the west coast of Australia material transfer would be restricted to an average of 113 days per year. Loading an OGV via a deep water port generally takes between 2 and 7 days while loading the same vessel via traditional transhipment normally takes in excess of a week under perfect conditions. The probability of a full week of favourable weather without interruptions is often slim, leading to unavoidable delays and expensive demurrage costs.

Traditional transhipment methodologies are often quite complicated and often involve 3 to 4 vessels. An OGV and a feeder vessel/barge are always required but if there is no materials handling equipment on board the feeder vessel or the OGV then a transfer barge will be required to facilitate the material transfer as shown in Figure 1.2. Under some circumstances there may also be the additional requirement to use tugs to bring the OGV alongside the transfer barge or feeder vessel depending on the manoeuvring capabilities of the OGV and feeder vessel. If unpowered barges are used as feeder vessels then a tug will also be require to manoeuvre these barges. Overall it is this level of complexity that often renders traditional transhipment uneconomical leading to production ventures being ruled unfeasible.

Figure 1.2: Photograph showing a side-by-side transhipment process that employs a materials transfer barge to transfer production from the feeder barge to the OGV. Note the requirement to have two tugs on standby. (SAMMI, 2018).

1.1.2 A better alternative?

The floating harbour transhipper (FHT) concept is being developed by Sea Transport Corporation with the aim of overcoming the limitations of traditional transhipment to offer an export solution that is as effective as a deep water port without excessive capital outlay. This allows mines that have previously been unfeasible due to location and lack of cost-effective export options to begin operations. The FHT concept is based around a mothership (the FHT) which houses material handling equipment, storage capacity and a large well dock for the feeder vessel, sheltering it from the incident sea state. Relocating the stockpile of bulk product to the FHT can significantly reduce the capital and operating costs by reducing the reliance on large, expensive sheds and wharf facilities onshore. It has been estimated that a transhipment solution can be operational in a quarter of the lead time of shore based infrastructure, resulting in earlier positive cash flow. The planning and approvals process for the construction of large coastal facilities are challenging, costly and lengthy. The FHT also provides environmental benefits of dust-free transhipment, eliminating grab spillage and dust issues while reducing costly dredging of sensitive areas. The FHT is also able to be easily relocated meaning that if a mine ceases production temporarily or permanently the FHT able to be repurposed to another venture.

The transfer process from shore to the FHT is comprised of three primary steps:

- Cargo is loaded onto a feeder vessel (up to 10,000 dwt capacity and approximately 4m draught) using a small harbour;
- The feeder vessel transits to the FHT, which is moored semi-permanently offshore in deep water, and enters the stern well dock;
- Cargo is transferred from the feeder vessel to be stored on the FHT until an ocean going vessel comes alongside for loading. Cargo can also be transferred directly from the feeder vessel to the OGV if one is alongside.

Figure 1.3 demonstrates the FHT concept: the three vessels are pictured, with the OGV (black hull) moored alongside the FHT (behind the OGV) and material is transferred directly from the feeder vessel (docked in well dock of FHT) to the OGV.

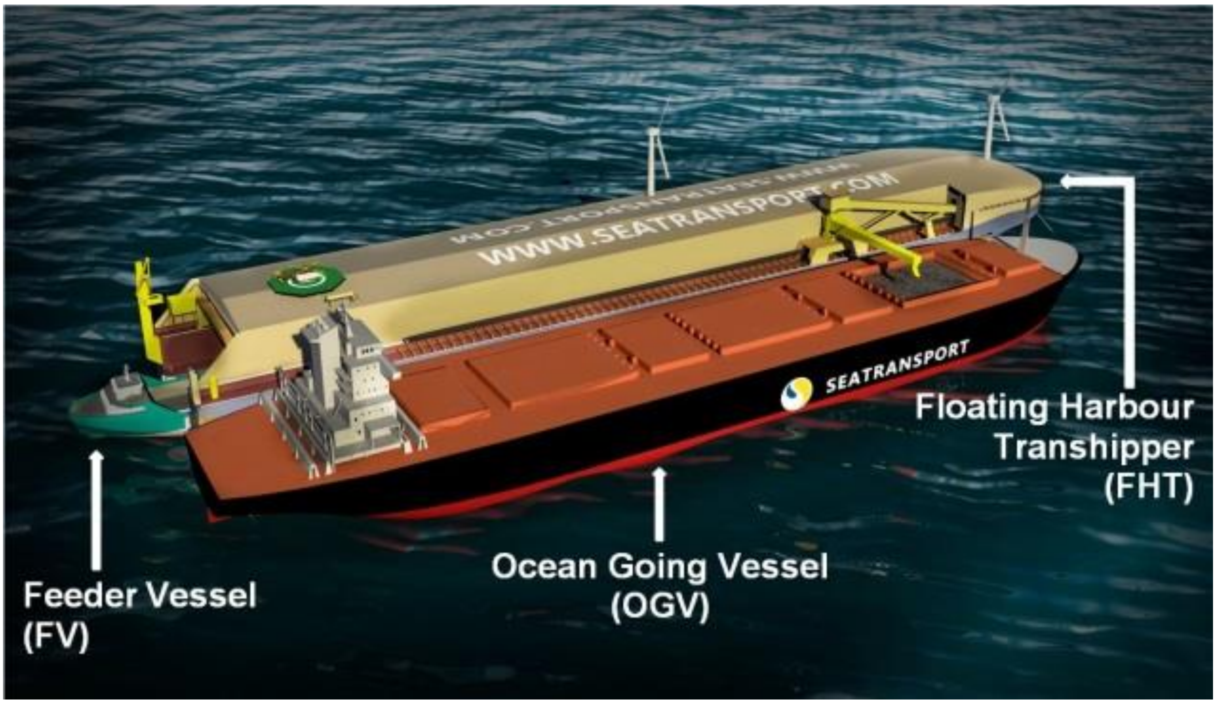

Figure 1.3: General arrangement of the FHT system showing the ocean going vessel (nearest), the FHT (behind OGV) and the feeder vessel (inside aft well dock of FHT, left).

The FHT is a large full-form, ship-shaped vessel designed to be moored offshore from the product export location and is fitted with thrusters to maintain heading control independently of the prevailing conditions. The principal dimensions of the FHT are similar to those of the OGV to be serviced and the cargo capacity is approximately 60% of the OGV capacity. The major innovation of the FHT concept is the stern well dock to provide shelter to a docked feeder vessel. The well dock aims to greatly reduce the relative motions between the feeder vessel and the FHT which will enable operations in a significantly wider range of sea states and facilitate purpose-built and faster material handling equipment similar to that used onshore.

The FHT concept separates the materials handling operations from the transport operations which allows the feeder vessel design to be focussed on the transport of bulk goods in a coastal environment and the FHT design to be focussed on materials handling and storage. This means that the ideal feeder vessel is essentially a small sized bulk carrier optimised to operate in shallow harbours with 4-5 m water depth and to transit through coastal sea states as economically as possible. For a Cape size OGV, approximately 13 feeder vessel loads are required to fill the FHT to full capacity; and around 20 loads to fill a typical ocean going vessel. The relatively simple feeder vessel reduces the shore facility requirements to a small shallow harbour, a negatively pressurized shed for the storage of a few days' stockpile of export material and material transfer equipment to load the feeder vessel.

Macfarlane, et al. (2012) presented a proof of concept study for the FHT concept which confirmed that the benefits obtained through the application of a well dock were considerable. The study investigated the motion of the feeder vessel when docked within the FHT in comparison with a traditional side-by-side transhipment configuration. In all cases there was a significant reduction in both pitch and heave motions of the feeder vessel, in some cases the pitch motions were reduced by as much as an order of magnitude. It was stated that the transfer of dry bulk cargo could be safely performed in 4 metre seas, potentially greater, resulting in a significant widening of the operational weather window.

In a feature article, the Australian Journal of Mining (AJM) discussed the pros and cons of eight different transhipment concepts, including the FHT (Foley, 2011). The article considered the capacity, capital expenditure, operating expenditure, stockpile, blending of cargoes and environmental impact of each concept. This discussion highlighted that the FHT concept has the potential to make transhipment more accessible to large volume offshore exporters. Ballantyne, et al. (2012), Macfarlane, et al. (2012) dug deeper into the benefits of the FHT concept with further discussion on the environmental benefits and an alternative application for disaster response to provide potential humanitarian needs. As previously mentioned, one of the significant environmental benefits of the FHT concept is the reduction in dust and materials transfer spillage compared to many traditional transhipment methods. With the FHT concept, bulk material is completely enclosed from the onshore storage facility up until transfer to the OGV which assists with maintaining a low transportable moisture level (TML). This is extremely important for ship safety as it greatly reduces the potential for liquefaction of the cargo, which is known to have resulted in the loss of many ships and crew(Andrei and Pazara, 2013, International Association of Dry Cargo Shipowners, 2016, Koromila, et al., 2013). Another major environmental benefit of the FHT concept includes the minimisation of dredging operations because the feeder vessel requires a relatively shallow draught. The need for road transport (and associated greenhouse gases) is also greatly reduced by using small harbours closer to the mine or export product. The FHT concept eliminates stevedoring damage to feeder and transhipment vessels and provides safe handling of inbound fuel and other dangerous goods, such as ammonium nitrate.

1.2 Hydrodynamic considerations

1.2.1 Multiple bodies in a seaway

The materials transfer phase of FHT operations involves the feeder vessel being docked within the well dock and restricted primarily in surge, sway and yaw, a certain degree of restraint in roll motion is expected but there is minimal restriction on the heave and pitch motions. When the feeder vessel is docked, product is unloaded from or loaded onto the cargo deck of the feeder vessel by a continuous barge unloader (CBU) which is similar in operation to a bucket wheel. This equipment requires the relative motion between the two vessels to be within a designed range. It is also important that there is no impact between the feeder vessel and the floor of the well dock as this could cause significant damage and hence unfavourable down time. Contact between the two vessels must also be considered during docking/departure operations in addition to the ability of the feeder vessel to safely and controllably enter/exit the well dock, preferably under its own propulsion. These operational considerations highlight the importance of understanding the ship-to-ship interactions occurring between the FHT and the feeder vessel.

Much of the published literature available on the topic of two vessels operating simultaneously in a seaway is centred on the offshore oil and gas industry. Research in this area often discusses mooring arrangement options, zero speed and arbitrary heading arrangements. The work of Zhao, et al. (2013) discusses the benefits of a tandem mooring arrangement as opposed to a side-by-side arrangement for FLNG and shuttle tanker operations. This field of research also includes the work of Hong, et al. (2005), Van der Valk and Watson (2005), Vepa, et al. (2012) and Choi and Hong (2002), which compare the performance of tandem and side-by-side mooring arrangements and associated mooring loads. Their research also discusses the application of numerical methods to the quantification of the seakeeping performance of multiple vessels operating in a seaway.

A number of publications have also focussed on lightering operations where two vessels are moored together in a side by side arrangement while moving slowly ahead and transferring liquid cargo. Lataire, et al. (2012) proposed an improved mathematical approach to modelling the forces that act on two vessels during lightering operations in shallow water. This paper used the experimental results of a 4 year project designed to build the knowledge base required to understand and simulate the hydrodynamic behaviour of two vessels during lightering operations. The results of the experimental campaign were summarised, discussed and used to successfully validate the proposed mathematical model. The methodology used for these experiments was discussed in detail within an earlier publication by the same authors (Lataire, et al., 2009). The article also identified earlier numerical approaches that have been applied to lightering operations, starting with methods developed from slender body theory to calculate the sway and yaw forces on two vessels moving ahead in deep water by Tuck and Newman (1976). Progress is discussed up to the unified seakeeping model of Skejic and Faltinsen (2007) and the successful application of this by Skejic and Berg (2009, 2010) to qualitatively predict the applied rudder angle during lightering operations. Xiang and Faltinsen (2010) further extended this method using 3D potential flow methods rather than slender body theory to account for arbitrary relative positions of the vessels and other structures. This was found to demonstrate good agreement to the experimental results of (De Decker, 2006).

1.2.2 Well docks

The aft well dock is the primary innovative design feature that unlocks many of the potential advantages of the FHT concept and solves many of the challenges faced by traditional transhipping. It is also one of the major challenges when it comes to understanding the hydrodynamic characteristics of the concept. The FHT interfaces with the feeder vessel by means of the aft well dock into which the feeder vessel docks astern to facilitate transfer of the bulk ore product by means of a continuous barge unloader installed on the FHT. The aft well dock in the FHT is open to the sea, has a solid bottom and is not sufficiently long to completely house the feeder vessel. Figures 1.4 and 1.5 depict the limited clearance between the feeder vessel and the well dock walls and bottom showing the solid well dock bottom and highlighting the potential for contact.

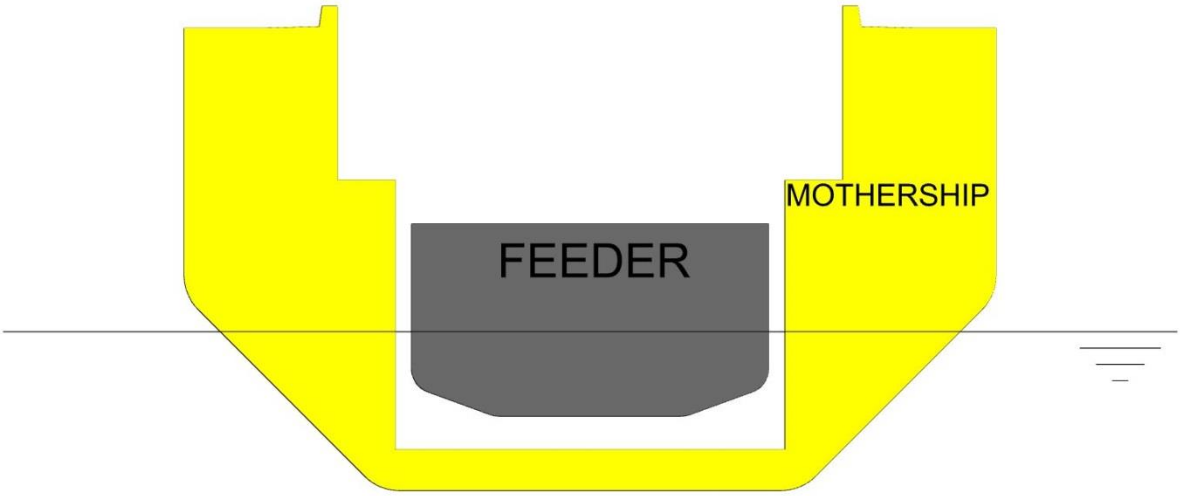

Figure 1.4: Relative difference between the feeder vessel and well dock cross sections for the present study, highlighting the limited clearance.

Figure 1.5: Plan view diagram showing the size of the feeder vessel relative to the well dock as compared to the LHD and landing craft system.

The solid bottom of the well dock was investigated during proof of concept studies presented by Macfarlane, et al. (2012) who conducted tests with and without a well dock bottom. It was concluded from physical scale model experiments that the removal of the bottom increased feeder vessel motion response, however the floor was found to introduce a potential impact scenario if large vertical motions are experienced. The enclosed boundaries (the walls and bottom) lead to an altered sea state being generated within the well dock which acts upon the majority of the feeder vessel with the bow section potentially being subjected to an external sea state that is influenced by the FHT hull form.

While well docks have never been applied in such confined applications in a sea state the application of well docks themselves is more common. Many of the world's navies employ well docks at the stern of Landing Helicopter Dock (LHD) amphibious assault ships such as Wasp, Mistral and Canberra classes to support landing craft operations (Glenys, 2017). It has long been recognised that it is far easier to embark (and disembark) a landing craft when it is in a sheltered harbour attached to the mothership rather than over the side of the vessel or during ramp-ramp transfers. However it has been found that when operating a smaller vessel within the well dock of a ship, the presence of a seaway introduces the risk of the smaller vessel striking the bottom of the well dock or overhead structure (Hopman, et al., 1994). It is also noteworthy that many of the well docks employed within amphibious assault ships incorporate a door across the opening that enables the area to remain dry if need be while the FHT well dock is not proposed to include the feature.

A number of authors have investigated well dock operations in a naval context using both experimental and numerical techniques. Most of these publications focus on the development of numerical simulation solutions for well dock operations on amphibious assault ships but Hopman, et al. (1994) employed an experimental approach in order to better understand a number of well dock design parameters. This study used an early iteration of the Dutch amphibious vessel (later commissioned as the Rotterdam class) and has become a baseline used to validate a number of numerical simulations that have followed. The authors focused on quantifying the wave environment within the well dock as this was considered the biggest hazard to controlled manoeuvring and embarkation/disembarkation in open ocean conditions. The effect of a number of well dock design parameters on the sea state within the well dock was investigated experimentally using a self-propelled model with the sea state within the well dock being measured relative to the well dock. Tests were conducted at two forward speeds for the amphibious assault vessel and in a full array of wave headings. Irregular sea states were employed with two significant wave heights and two zero up-crossing wave periods.

Lee and Wu (1999) undertook a numerical investigation on the Singaporean navy's amphibious assault vessels with the aim to quantify the wave environment within the well dock. A similar study was undertaken for the Canadian navy by Bass, et al. (2004) whom employed a potential flow code coupled with a commercially available CFD solver to investigate fluid behaviour inside a well dock. They described the development of a CFD approach to the prediction of the sea state within the well dock of an amphibious vessel. Three levels of numerical complexity were considered during development of a fully coupled CFD and ship motions code, taking note of the effect of the motion of the amphibious assault vessel on the sea state and the effect of the sea state on the motion of the vessel at each time step. By assuming the sea state inside the well dock had negligible effect on the motion of the vessel (and by extension the external sea state), the coupling effect can be ignored and the computation time significantly reduced. This allowed the internal sea state to be simplified to a wave generated at the entrance of the well dock based on the vessel motion. These simplifications provided satisfactory results when compared to available experimental results.

Cartwright, et al. (2006) investigated the motion response of a landing craft within an amphibious vessel using the mesh-free numerical technique, smoothed particle hydrodynamics (SPH). The aim was to develop a numerical methodology for predicting the relative motion of the two vessels which would enable the operational window for well dock operations to be defined. Two scenarios were investigated; the landing craft tethered within the well dock, and the landing craft moving forward into the well dock until it contacted the beach at the forward end. Two landing craft load conditions were modelled representing the vessel at full and empty cargo capacities. It is of particular relevance to the current research that the well dock discussed is a similar size and proportion relative to the amphibious assault vessel as the FHT's well dock is to the FHT (ie. a very crude 'geosim'). The tethered condition discussed is analogous to the situation where the feeder vessel is docked within the FHT, however there is a large difference in the sizes of the landing craft and feeder vessel relative to the respective well docks. SPH was successful in determining the relative motions between the vessels and showed that contact between the landing craft and the well dock floor is a potential issue, but it was acknowledged that there was still verification and validation required before wholesale application.

Cartwright, et al. (2007) extended the abovementioned study by employing SPH to capture the unique hydrodynamics occurring inside the well dock to better understand how the landing craft was affected. Three primary design traits were investigated: the depth of the well dock, the slope of the well dock bottom and the inclusion of a door at the entrance to the well dock. The primary dataset presented was free surface elevation measurements at various locations within the well dock. The limitations of this numerical approach are acknowledged to be mainly related to limited domain size or relatively coarse grids. The numerical results were compared to experimental data and good agreement was observed, particularly at the aft end of the well dock (near the entrance). It was noted that the wave environment was more favourable when the floor was sloped upwards towards the forward end of the well dock. The depth of the dock was found to have little effect on the wave environment surrounding the landing craft and the removal of the door at the aft end of the well dock was found to improve the wave environment.

The amphibious vessel and landing craft systems exhibit significant clearance between the landing craft and the well dock walls. This leads to the behaviour of the landing craft being predominately dependant on the artificial sea state inside the well dock. The FHT concept on the other hand, involves a much larger feeder vessel to well dock cross sectional area ratio as demonstrated by Figure 1.5. This notable reduction in clearance is not only unique in maritime operations, but it also poses another challenge when the feeder vessel enters (or exits) the well dock as the large volume of water that must be displaced creates some interesting confined water effects.

The only published literature (prior to the current research project) concerning a vessel that causes significant blockage entering a well dock is a proof of concept study for the FHT performed by Macfarlane, et al. (2012) and Ballantyne, et al. (2012). This was a pilot study ahead of the current research project and focussed on the seakeeping performance, with the primary aim to explore the viability of the FHT concept to justify future development and investigation. This initial study involved scale model experiments comparing side-by-side seakeeping performance to docked seakeeping performance which demonstrated an order of magnitude improvement in pitch and roll (as previously noted).

1.2.3 Well dock ventilation

The use of a well dock provides a sheltered zone for the feeder vessel in order to reduce the relative motions between the vessels, however it also yields a unique confined water scenario while docking the feeder vessel. The limited beam and under keel clearance of the feeder vessel operating inside the well dock will almost certainly yield unfavourable confined water effects. Basic flow calculations indicate that expected flow velocities under and along the sides of the feeder vessel as it docks or departs will have a measurable effect upon the feeder vessel. The velocity of the water flow will be significantly greater than, and predominantly in the opposite direction to, the feeder vessel speed - posing further challenges given the propulsors must operate in this complicated environment. The resultant changes in pressure will in turn affect the bodily sinkage and trim of the feeder vessel and the force required to move it creating challenges to safe and controlled manoeuvring. It is hypothesised that if these velocities could be reduced then the flow complexity and ship-to-ship interactions could be reduced.

An effort has been made to do this by incorporating a pair of vents in the side of the well dock within the parent hull design of the FHT. These vents are positioned at the forward (closed) end of the well dock below the still water line (refer to Figure 1.6a) and permit the entry of water into the well dock as a feeder vessel exits and vice versa. For a Cape size FHT, when the feeder vessel enters the well dock more than 10,000 tonnes of water must escape to make way for the entering feeder vessel. This represents approximately 55% of the total water volume contained within the well dock that must flow back past the entering feeder vessel, or partly through the vents and partly past the feeder vessel. The reverse is then the case when the feeder vessel departs – a large volume of water must enter the well dock (it is acknowledged that in one of these operations, entry or exit, the feeder vessel is likely to be in a light condition having transferred its cargo).

These vents have been included in the parent hull design as an intuitive response to the confined water scenario based on findings that were observed during proof of concept scale model experiments performed using a removable well dock floor. The inclusion of such vents is to the author's knowledge unprecedented in published literature and is a significant departure from the well dock geometry that is observed within amphibious assault vessels. The vents proposed were sized with consideration of the blockage that is generated by the feeder vessel and the structural design of the FHT.

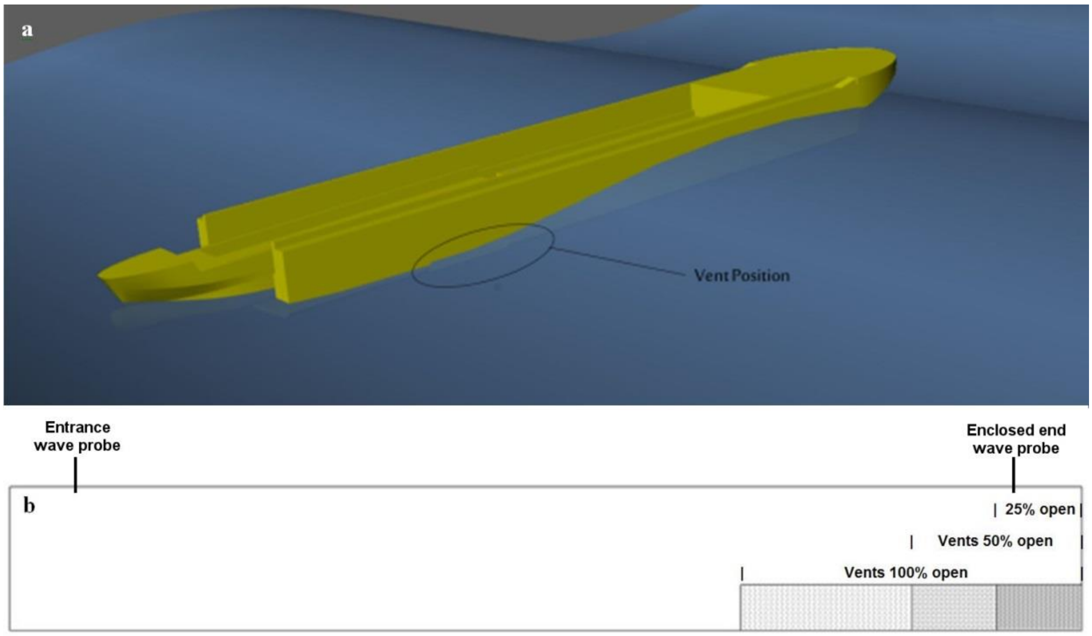

Figure 1.6: (a) Render of the mothership with the feeder vessel docked within the well dock showing the location of the well dock vents below the water line. (b) Profile view of just the well dock (page-wide box) and vent configurations to illustrate the relative sizes: 100% open (all shaded areas), 50% open (two darker shaded areas) and 25% open (the darkest shaded section). Note: vents were present on both sides of the mothership well dock.

The effectiveness of the vents in mitigating the extreme confined water scenario requires significant further research which forms a large component of the current project. With virtually no prior relevant investigations, the logical approach was to include a systematic variation in vent size, covering a practical and logical range. The maximum size, referred to as 100% open, is roughly equivalent to approximately 1.8 times the immersed amidships cross sectional area of the feeder vessel at the full load condition. Four different vent scenarios were selected for this study: 100% open, 50% open, 25% open and no vents. The vent configurations are depicted in Figure 1.6b. There are significant structural and buoyancy considerations when cutting significant areas out of the bilge of the vessel. These considerations coupled with the effects of the large well dock at the stern of the vessel highlight the importance in investigating the relationship between well dock vents, seakeeping performance and manoeuvrability during docking.

Well dock vents are largely unprecedented but an analogous concept was found to be culvert systems in a coastal breakwaters. Culverts are penetrations through breakwaters used to enable flushing to avoid silt build up in sheltered areas and differential water levels across the breakwater. Tsoukala, et al. (2014) investigated the effect of size of culverts in coastal breakwaters that were vertically centred on the still waterline. At the time it was global practice to have the culverts fully submerged below the free surface. The highly variable nature of the wave parameters were discussed, in particular the significant effect these have on the wave energy. It was found that the turbulence within the wave and the wave frequency had the greatest effects on the energy transmission through the culvert. It was interestingly noted that while the height of the culvert had very little influence, increased culvert width lead to an increase in wave energy transmission through the culvert. The vents in the well dock of the mothership are intended to be fully submerged under most operational conditions and the mothership itself will be floating as opposed to the rigid breakwater. The most applicable finding from Tsoukala et al.'s work to the current research is that the height has very little effect on the energy transmission but the length of the vent has a direct correlation to energy transmission through the vent.

1.2.4 Confined water considerations

Some challenges in applying existing knowledge of amphibious assault vessels to the FHT concept stem from the naval application of these vessels which can hinder the dissemination of more broadly applicable data. All of the available studies have also been based on the well dock operations of an amphibious assault vessel with a focus on the interaction with landing craft. Numerical simulation approaches presented were found to be successful for cases that had similar well dock dimensions and proportions to the FHT, however, the landing craft that operate within an amphibious assault vessel's well dock are far smaller relative to the well dock than the feeder vessel proposed for the FHT. This leads to significant differences in the confined water effects between concepts.

The confined water effects within the FHT concept must be considered with respect to two key operations; docking/departing and materials transfer. The feeder vessel must be able to enter and exit the FHT well dock under the influence of a seaway, an operation that spans across two important hydrodynamic phenomena. Initially ship-to-ship interactions will affect the feeder vessel and FHT while the feeder vessel is approaching the FHT and once it begins to enter the well dock then the effects of moving through the confined water must be overcome. This is similar to other confined water scenarios such as those seen when a ship enters a narrow channel or lock. The feeder vessel must also be able to be loaded and unloaded when it is docked within the FHT in sea states larger than is currently possible with traditional transhipment methods. The effect of the confined water on the seakeeping performance of the two vessels, particularly the relative motion, while docked must be understood in order to extract the maximum benefit from the FHT concept.

The confined water situation that occurs when the feeder vessel enters or exits the well dock of the mothership is unique to this application but there are similarities to previous publications on topics such as a vessel operating in a narrow river, channel or lock. Published literature on these topics is plentiful and assists in developing a foundation understanding of the hydrodynamic phenomena within the well dock. Much of this discussion is in the context of river and lock situations using an assortment of experimental and analytical methods. Most of these studies build upon one dimensional investigations of vessels transiting canals in calm water (Constantine, 1960, Sjostrom, 1967, Tothill, 1966). Other relevant investigations on confined water effects were undertaken by Sharp and Fenton (1968) who performed experiments on shallow water effects observed in the Yarra River and Tuck and Taylor (1970) who further investigated squat effects and wave forces in regular beam seas in shallow water.

Vessels operating in locks are often subject to very limited lateral and under keel clearances, similar to the feeder vessel operating in a well dock. Ship behaviour in locks was the focus of the 3rd International conference on ship manoeuvring in shallow and confined water which provides a wealth of published literature on the topic Vantorre, et al. (2013). CFD simulations have since been undertaken by Toxopeus and Bhawsinka (2016) to investigate the hydrodynamic interaction forces on a large-beam vessel entering the Pierre Vandamme Lock. In addition to force data, the authors presented velocity fields around the vessel which give an insight into the flow fields expected within the lock.

The limitation of these studies being applied to well docks is that there is no incident seaway and most studies consider channels of infinite length. However, the FHT concept has the added complication of an incident seaway. This may relate more closely to the proposed ship tunnel in Stad, Norway (Rahim, 2017) and other canals that open to ocean environments where there is limited water depth at the entry and/or exit of the tunnel.

1.3 Problem definition and research questions

The feature that gives the FHT system its advantage over other transhipment methodologies also generates a unique and challenging hydrodynamic scenario that warrants investigation before being put into practice. The cross sectional area of the feeder vessel is a significant proportion of the cross sectional area of the well dock that it is entering causing a high blockage coefficient. By better understanding the behaviour of a vessel operating within a well dock that has a cross sectional area only marginally larger in size than the entering vessel it is possible to unlock the operational efficiencies of such a concept.

The significant blockage coefficient combines with the enclosed nature of the well dock to produce a confined water scenario similar to a river lock. An incident seaway acting on the whole system further complicates the docking/departure manoeuvres as well as the materials transfer operations. The differences that separate the operation of the FHT concept from river lock scenarios are that the FHT is free floating, subjected to an incident sea state and the geometry surrounding the well dock is very different. There is published literature on the topic of vessels entering highly confined locks however there is limited discussion on the topic of a vessel entering the well dock of a vessel that is free floating. This topic is limited to well docks that have been employed in naval applications on various amphibious assault vessels. Well docks are used to provide a safe and sheltered environment to embark landing craft while the amphibious assault vessel is at sea. The landing craft entering the well dock is significantly smaller, approximately one quarter of the size of the well dock. This disparity in cross sectional areas means that confined water effects are of lesser consequence.

The specific application of well docks to transhipment in quite exposed environments leads to a very novel solution to an age old problem and positions this research in a significant knowledge gap. A large proportion of the design work performed on the FHT concept prior to the commencement of this project was based on intuition and basic understanding of confined water effects. The current project was launched to fill this gap using a number of experimental investigations to develop the understanding of the ship to ship hydrodynamics required to prove the FHT system viable.

This PhD focusses on two key operations of the FHT system that are important to successful transhipment operations; the materials transfer phase where the feeder vessel is docked within the well dock while exposed to an incident sea state and the docking/departure process whereby the feeder vessel manoeuvres within the well dock. It is important to understand the relative motions between the vessels as this behaviour differs from existing ship-to-ship interactions and feeds into the materials handling equipment design and weather window determinations which are key to the success of the concept. The docking/departure manoeuvres again differ from previous confined water operations and this knowledge improves the safety of the feeder vessel and extends the understanding of extreme confined water operations.

The significant confined water effects were expected during the preliminary design work on the concept. These effects were targeted by the introduction of a pair of vents at the forward (closed) end of the well dock which were intuitively designed due to the lack of empirical data at that time. The necessity and effect of these vents are also central to this PhD project as this knowledge is necessary to properly understand and effectively apply well docks in transhipment operations.

This research project broadly aims to investigate the hydrodynamics of a feeder vessel operating in a well dock and to determine the effect on the motion response and manoeuvring characteristics of a feeder vessel. The ability of well dock vents to improve the hydrodynamics in a transhipment context is also central to the research project. This thesis answers two key research questions;

- What is the influence of the feeder vessel when docked within the well dock on the seakeeping performance of an FHT and the feeder vessel, and to what extent does well dock ventilation alter this effect?
- What are the hydrodynamic interaction effects between the feeder vessel and the FHT when the feeder vessel is manoeuvring within the well dock, and to what extent can these effects be mitigated using vents at the forward end of the well dock?

1.4 Methodology

The objectives and research questions posed by this study are addressed using a series of physical scale model experiments. All physical scale model experiments (except where explicitly stated) discussed within this thesis were designed and executed by the candidate. The construction of models was outsourced to specialist contractors and the manufacture of PIV particles was undertaken by staff with specialist experience. The candidate actively led all other experimental activities seeking supervision or guidance where training or safety protocols were required. The unique hydrodynamics of two vessels operating in such close proximity limits numerical simulation options. If a numerical solution were to be implemented a significant level of validation would be required to prove the reliability of the method. Being essentially the first in-depth study into this unique hydrodynamic scenario warrants an experimental campaign that could later be used to validate numeric tools for design and optimisation applications. A range of numerical approaches were considered and attempted during the course of this project including multi-body potential flow solutions and mesh free techniques such as SPH. These methods have seen prior application in similar situations but where not feasible in the context of the current project.

An attempt was made to use a panel method potential flow solution that supported multiple bodies that is currently being successfully applied to replenishment at sea (RAS) operation simulations in a naval context. This numerical approach was able to perform frequency domain simulations and combine these to create a resource efficient time domain simulation of two moving vessels that are separated by a reasonable distance (in the order of a vessel beam). This method uses artificial lid approaches to suppress unrealistic interaction between the multiple surface elevation components and has been experimentally validated for several naval applications. To apply this approach to the fuller formed vessels of the current project was going to require further experimental validation and early tests to predict the interaction between the vessels indicated that the software required further development to successfully validate the small clearance scenarios required.

The application of SPH to this project was initially a separate PhD project within the larger project team and early validation simulations of simple configurations showed promise. Unfortunately as simulations of more complex elements of the project were attempted, the domain grew and the resolution requirements were so large that the computational requirements were greater than the resources available. Much later in the project and after the experimental investigation had been completed, an external party was contracted to use SPH to simulate a handful of the experimental runs and validate these against the docking experiments in Chapter 3. Once again there were very significant simplifications required to achieve a computationally feasible simulation and these results were found to not yet represent the physical experiments.

Scale models of all three vessels were constructed at a 1:60 scale as depicted in Figure 1.7. The models seen in this figure were photographed in the Australian Maritime College's (AMC) finite depth wave basin at the conclusion of the project, where superstructure was added to each model and more realistic livery applied in an attempt to better simulate the proposed concept. The superstructure was removed and a number of hull markings over a single colour paint scheme were adopted during the testing phases. This facility and the models shown were used for the vast majority of the experimental investigation within the project. All experimental testing was performed in a scale water depth that represented 20m full scale (333 mm at model scale).

Figure 1.7: Photograph of the three physical scale models showing the general arrangement of the FHT system. The black hulled ocean going vessel (OGV) is nearest the camera, the green hulled FHT (mothership) is behind the OGV and the bow of the feeder vessel (navy blue hull) can be seen protruding from the stern well dock of the FHT (left). Some of the materials handling equipment onboard the FHT for transfer to the OGV can be seen.

The majority of the experimental investigation presented within this thesis can be split into two main stages; docked seakeeping operations and the docking/departure operations. These two operations required different experimental approaches using different apparatus. The docked seakeeping investigation was undertaken first due to the more conventional nature of these experiments. The feeder vessel was docked within the mothership and secured using a ball and slider to model the proposed coupling between the vessels and the combination was held in place within the basin using tethers attached to posts fore and aft. A number of regular head sea wave periods were investigated across three full scale wave heights of two, four and six metres full scale. One loading condition was considered for the mothership and feeder vessel that represented the worst case scenario: with the feeder vessel at full load displacement (deepest draught) and a lightly loaded mothership condition (shallowest water depth within the well dock). There was no OGV model alongside during this study.

During the seakeeping experiments both vessels were tracked in six degrees of freedom using a Qualisys digital video motion capture system and the incident sea state was measured at a number of positions within the basin. Analysis focussed on the heave and pitch motions of the vessels as the surge was restricted and the yaw, roll and sway are not of relevance in the head seas case. The clearest indication of seakeeping performance was the under keel clearance between the feeder vessel and the well dock floor in the time domain as contact between the two vessels could cause significant damage to both vessels and lead to down time.

The docking/departure manoeuvre investigation began by rigidly mounting the mothership model to the basin floor to restrict it in all six degrees of freedom whilst the feeder vessel was attached to the towing carriage and towed into (and out of) the well dock using a prescribed velocity profile. The feeder vessel was constrained in surge, yaw and sway while remaining free to heave pitch and roll, each of which was measured relative to the mothership. A pair of tow posts included six-axis load cells that enabled the measurement of the surge and sway forces and yaw moment. The Qualisys motion capture system was again employed to record the feeder vessel's longitudinal position during the manoeuvres and a rotary encoder provided the vessel speed profile.

The analysis of this experiment focussed on the longitudinal force and the dynamic vertical motions (sinkage and trim) experienced by the feeder vessel throughout the manoeuvre. These parameters are important as they give an indication of the controllability and propulsive requirements of the feeder vessel when docking as well as indicating if there are potential contact issues between the vessels.

Also of significant interest is the fluid flow that causes these variations in feeder vessel motion and thrust requirement. While the understanding of this flow behaviour is crucial to understanding the effects of vent size, flow visualisation is both complex and resource intensive to obtain for such a complex situation. For these reasons a separate set of experiments were undertaken to collect flow visualisation data. Laser measurement techniques, namely Particle Image Velocimetry (PIV), was employed to record the flow behaviour inside the well dock during docking and departure manoeuvres. The mothership model was exchanged for a simplified Perspex representation of the well dock and vent geometry to enable the transmission laser light through the walls of the well dock. The feeder vessel was towed into the well dock model in the same manner as the first stage of the docking/departing experiments. The analysis of the flow field focussed on the flow velocities on a plane half way between the well dock bottom and the keel of the feeder vessel. This covered the most important regions where the feeder vessel propulsors operate within the closed end of the well dock, and around the vent opening.

All experiments have been conducted by following the relevant International Towing Tank Conference (ITTC) recommended procedures and guidelines as closely as possible. The data integrity of all results, and most importantly trends, presented in Chapters 2 and 3 have been enhanced by conducting an uncertainty analysis, as presented in the Appendix. This process indicated what variances between data series were conclusive and which variances were within the uncertainty band of the measured data. Due to the quantity of data presented on many of the experimental comparison plots and the application of distinguishing symbols the addition of error bars was often found to significantly affect the clarity of the figures. The post processing tool employed to process the PIV data presented within Chapter 4 contained an uncertainty tool that was used to ensure the flow fields presented were only drawn from good quality images that produced low uncertainty levels.

1.5 Novel aspects

This project provides significant contribution through the investigation of a novel and unique application of well docks to transhipment. The well dock concept investigated differs from all previously investigated configurations due to three major features: (1) the feeder vessel is only slightly smaller than the well dock in which it docks, leading to unique and interesting confined water hydrodynamics; (2) the entire system is subjected to an open ocean sea state and the sheltering effect that the mothership is able to impart on the feeder vessel is limited by the seakeeping performance of the mothership itself, and (3) the introduction of vents to a well dock has not been attempted before (and available in the public domain).

The considerable differences between the proposed transhipment concept and relevant existing operations have been described in preceding sub-sections. Developing a deeper understanding of the unique scenarios posed by this concept has required an investigation that involves several programs of complex physical scale model experiments using a wide range of traditional and advanced measurement techniques. The acquired data has been post-processed and analysed to gain insights into key aspects of well dock hydrodynamics and feeder vessel-mothership interaction which should improve the prospects of this novel transhipment concept being adopted by industry. All aspects investigated within this project have application beyond the development of well dock based transhipping and well dock/mothership operations.

Several key areas of tangential published areas of study are being drawn together and further investigated in the context of the FHT concept;

- Previous well dock operations that are subject to incident sea states have focussed on naval applications with much smaller blockage coefficients (5-10% by cross sectional area based on approximations from publicly available information) transferring materials via ramps. This research extends this application to understand much higher blockage coefficients (60% by cross sectional area) and much more sensitive materials transfer methods. The focus will also shift from ensuring the system functions safely to striving for improvement in material transfer rates.
- Previous confined water publications that have similar degrees of blockage and length restriction are focussed on canal and river locks. No existing literature has discussed the influence of a sea way on a scenario exhibiting this level of blockage. This project investigates the effect of a seaway with zero forward speed and builds the foundation required for further investigation into the docking and departure manoeuvres when an incident sea state is present.
- The study of relative motions between two vessels of this scale has previously been restricted to side by side and tandem arrangements. This study considers the scenario where the feeder vessel is operating inside the mothership, creating a vastly different hydrodynamics scenario.
- Transmission of waves through an opening in a solid structure has previously been considered in the context of culverts through a breakwater. Openings such as the well dock vents have not previously been investigated in the application of a free floating vessel in a seaway as a mechanism for mitigating confined water effects.

1.6 Thesis outline

To achieve the overarching goal of understanding the hydrodynamics of a feeder vessel operating within a highly confined well dock the two major operational scenarios were investigated in isolation before a compromise could be reached to satisfy all aspects. The chapters follow the process undertaken to investigate and understand the unique hydrodynamics surrounding the FHT concept.

Chapter 1: Presents the processes currently available for the transportation of bulk goods and introduces the FHT as a better alternative to traditional transhipping. The unique well dock application that gives the FHT its advantage are explored in detail and the reader is orientated with the operation of the FHT. Published literature in appropriate tangential fields that can provide a foundation for the present research is discussed.

Chapter 2: Discusses the seakeeping performance of a generic feeder vessel and mothership while the feeder vessel is docked within the well dock. The methodology used to conduct the experimental investigation and the results obtained are discussed before relating these back to the operational aspects of the FHT. The relative motions between the vessels are identified and discussed as the most important parameter from an operational view point.

Chapter 3: Presents the initial experimental process undertaken to explore the docking and departure manoeuvres. The experimental study was constructed around a generic well dock and feeder vessel followed by discussion to apply these findings to the operational process of the FHT. This chapter focusses on the effect of the well dock and vents on the control and manoeuvrability of the feeder vessel by interrogating the force and motion response data. Key areas of interest and particular trends were identified as anomalous and explanation was sought from fundamental literature.

Chapter 4: Presents a deeper investigation into the flow behaviour that causes the interesting behaviour of the feeder vessel while docking in and departing from the well dock. The generic well dock and feeder vessel experiment is developed to enable the application of PIV techniques. The flow field within the well dock is analysed to understand what is causing the feeder vessel behaviour and how the vents are mitigating the confined water effects.

Chapter 5: Presents a summary of the work done, conclusions formed and provides suggestions for future work.

CHAPTER 2

Seakeeping performance of a feeder vessel docked inside the well dock of a mothership

2.1 Introduction

The aim of the investigation presented in this chapter is to improve our understanding of the seakeeping behaviour of a feeder vessel when it is docked within the well dock of a mothership, such as that proposed within the FHT concept. A key initial objective is to determine if the motion response of a feeder vessel is more favourable when docked inside a well dock than in open water or alongside an ocean going vessel. This will enable a judgment to be made on the feasibility of the mothership with well dock concept as an alternative to traditional transhipment arrangement.

Each of the three scenarios is influenced by different sets of variables. The feeder vessel operating independently will be influenced solely by the incident sea state. The feeder vessel when operating alongside the mothership will be influenced by the incident sea state which will be altered by the presence of the mothership and the interaction effects between the feeder vessel and the mothership. Finally the feeder vessel when docked within the well dock will presumably be less affected by the incident sea state due to the intended sheltering effect but will have more complex and unknown interactions between the two vessels within this unique environment.

The feeder vessel performance when docked within the well dock is going to be affected by several variables such as the period, amplitude and heading of the incident sea state, the water depth within the well dock, the motion of the mothership itself, and the relative size of the two vessels. The sea state parameters will have a significant effect on the motion of the mothership as well as the feeder which in turn will further alter the performance of the feeder vessel. In a simpler case where the dock sheltering the vessel is stationary, the effect on the seakeeping performance of the feeder vessel is almost always an improvement across all variables. The variability of the situation where the well dock is also attached to a floating vessel makes this prediction much less reliable. The added possibility of having the two vessels collide also adds a further critical data point; the relative motion between the two vessels which is much more difficult to predict than the motion response of one vessel.

Once a baseline seakeeping performance for a vessel docked within a well dock is determined, further investigation into the influence of vents within the well dock can be performed. It was hypothesised that the inclusion of vents within the well dock would be required to reduce the complexity of flow within the well dock as the feeder vessel enters and departs (refer Section 1.2). This will provide a better understanding of the effect of fluid ventilation on the seakeeping performance of a docked vessel and provide guidance for well dock design. The primary quantification of seakeeping performance are the relative motions between the feeder vessel and the mothership as this will be a crucial factor when loading or unloading the feeder vessel. The worst case under keel clearance between the feeder vessel and the well dock floor in the time domain is the most crucial factor as contact between the two vessels could cause significant damage to both vessels and lead to down time.

Physical scale model experiments were employed for this study as it is a proven method for determining the motion response of vessels when under the influence of complicated hydrodynamic phenomena. The range of investigation is limited to head seas and a single (worst case) load condition for each vessel. This is justified as (a) it is intended that the mothership be equipped (ie. stern thrusters) with the means to maintain the most favourable wave heading (usually head seas) and (b) it is commonplace to focus on the worst case scenario for vessel loading. While it is currently proposed that the mothership is intended to have the ability to maintain heading, the effect of these thrusters is outside the scope of the present investigation.

2.2 Physical model scale experiments

2.2.1 Scope of testing

The investigation commenced with a proof of concept study to compare the feeder vessel motions in the same incident wave conditions for three different scenarios: in open water; alongside an ocean going vessel and docked inside the mothership well dock. First the effectiveness of the well dock at improving the seakeeping performance needs to be characterised. Once the advantage of the well dock concept has been proven the effect of the vents could be investigated. For this initial study into the seakeeping of the concept, the wave conditions focussed on a single wave heading of pure head seas relative to the mothership and two different incident regular wave heights equivalent to 2 and 4 m full scale across a range wave periods from 6.7 to 19.8 s full scale. These wave conditions in the full scale water depth of 20 m placed all tested sea conditions within the intermediate wave regime. This is generally representative of typical sea conditions for a large percentage of the Australian coastline from the north-west to the south-east (anti-clockwise), where there are numerous remote locations that could potentially adopt the FHT concept. The two vents (one each side of the mothership) were varied across four different configurations: (a) vents 100% open, (b) vents 50% open (c) vents 25% open, and (d) no vents. The total cross sectional area of both vents for the vents 100% open condition is equivalent to approximately 1.8 times the immersed amidships cross sectional area of the feeder vessel at the full load condition. The novelty of this concept meant there was little prior knowledge in which to estimate suitable dimensions for the largest (100%) open vent case for this investigation. The dimensions selected are based on the assumption that the cross sectional area of the vents is significantly more than that of the feeder vessel. The inclusion of the two smaller vent sizes, 50% and 25%, are logical increments from which to form a basis of comparison in performance.

The vessel conditions are considered to represent a realistic worst case scenario, with the feeder vessel at full load displacement (this is intended to be the scenario for every case during normal operations) and the mothership at a light load condition. This combination presents the minimum practical under keel clearance between the keel of the feeder vessel and floor of the well dock (refer to Figure 1.4).

The motion of both the feeder vessel and mothership in all six degrees of freedom and wave elevation measurements at three key locations along the length of the test basin were measured. Vessel motion was measured using a Qualisys motion capture system consisting of eight Oqus 700+p cameras. This system tracks a small number of markers that are rigidly attached to each vessel model. Under the assumption of a rigid model the Qualisys Track Manager software uses the triangulated position of these markers and trigonometry to output the motion of the vessel in six degrees of freedom. Of the six degrees of freedom motion data collected, it is the pitch and heave motions that are of primary interest to this investigation due to the direction of the incident sea state and the limited scope for lateral motions when the feeder vessel is docked.

2.2.2 Facility and apparatus

The experiments were conducted in the finite water wave basin at the Australian Maritime College (2017) using 1:60 scale models of a mothership and feeder vessel. The model of the mothership was moored using standard horizontal fore and aft lines made of 3 mm diameter paracord to maintain the nominal heading at 180^o (head seas) while having negligible effect on the vertical motions. The forward mooring line was attached to the bow of the mothership model and a fixed post at least one vessel length in front of the model. The stern of the mothership was attached to a stern line by means of a V-shaped bridal at the water line. The stern line was then redirected into the vertical plane by means of pulleys which allowed the line to be weighted with sufficient mass to minimise surge motions when under the influence of waves. The forward line tension was monitored during test runs in order to detect a slack condition. A schematic of the physical test set up is shown in Figure 2.1.

The feeder vessel model was constrained within the well dock using a ball and slider connection that allowed free motion in heave, roll, pitch and yaw to the limits allowed by the walls of the well dock. The ball and slider coupling between the feeder vessel and the mothership is outlined in Figure 2.2. This mooring arrangement restricted any surge motion between the two vessels, which is seen to be a reasonable representation of the intended real world situation. The sway of the feeder vessel was restricted relative to the mothership and this is also consistent with the real-world situation, given the deliberately limited clearance available (it is likely that fenders would be inserted between both sides of the feeder vessel and the well dock near the entrance. The yaw and sway motions of the vessels in a global sense were significantly reduced and damped by the soft mooring system restraining the mothership which was acceptable as neither of these motions were deemed to be of significant influence to the objectives of testing due to the intended ability of the mothership to control yaw using stern thrusters.

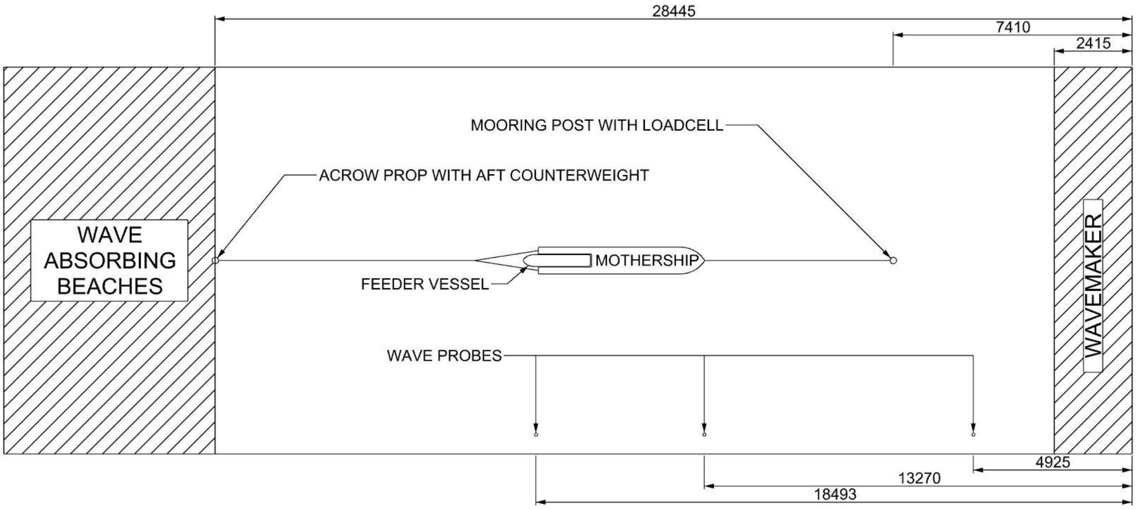

Figure 2.1: Plan view schematic of the experimental layout as used for the docked seakeeping experiments showing the mooring arrangement and wave probes (all dimensions in mm).

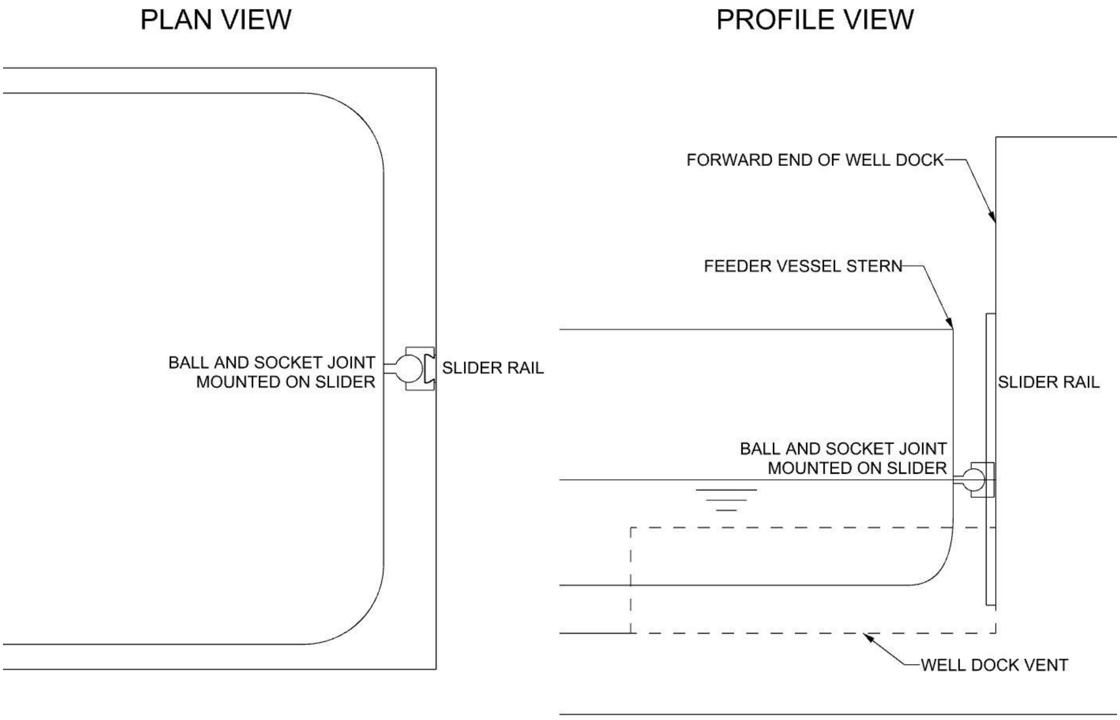

Figure 2.2: Plan (left) and profile (right) views showing the coupling between the feeder vessel and the mothership.

Three two-wire resistive wave probes were employed to measure the incident wave profile at three key longitudinal locations in the basin, as shown in Figure 2.1. These wave probes monitored the waves produced close to the wave maker as well as the incident waves at the bow and the stern of the mothership. These wave probes were sufficiently spaced transversely such that no radiated or diffracted waves from the models were present during the measurement period. Wave probes were also employed inside the well dock during FHT alone testing in order to characterise the wave field inside the well dock. A wave probe was located on the centreline of the FHT and approximately 5% of the well dock length forward of the entrance to the well dock for all vent conditions to enable comparison of the wave fields.

2.2.3 Model conditions

The principal particulars of the two 1:60 scale models used in the current investigation are presented within Table 2.1. The loading conditions represent realistic mass distributions for the target conditions.

Table 2.1: Principal particulars of the hull forms used in the experiments.

	Mothership		Feeder Vessel	
	Ship	**Model**	**Ship**	**Model**
LOA [m]	315	5.250	125	2.083
Beam [m]	50	0.833	22	0.367
Draught @ LCF [m]	11.556	0.193	5.190	0.087
Displacement [t]	107698	0.499	11284	0.051
Trim [degrees]	0	0	0	0
VCG [m from keel]			9.350	0.156
LCG [m from transom]			57.810	0.964
Pitch Gyradius [m]			34.740	0.579

2.3 Results

The test program was designed to focus on operations when the sea state is in the order of 2 to 4 m, as these conditions are relatively common for the typical regions where transhipment operations occur. These sea states are also generally at the upper limit and beyond conventional side-by-side transhipment operations, but represent the zone where the mothership-feeder vessel concept can potentially provide a significant reduction in down-time due to adverse sea conditions. For these wave conditions it is intended that the mothership use stern thrusters (if required) to maintain a head sea orientation, significantly reducing the likelihood of any notable roll, sway and yaw motions.

Due to these factors the focus of discussion of seakeeping performance is primarily on the heave and pitch motions of the feeder vessel and mothership. The heave and pitch motion data is presented as peak to peak amplitudes of the cyclic motion recorded during the steady-state period of experiment. All the measured peak to peak amplitude values for both the heave and pitch motions of the vessels are non-dimensionalised, with the heave motion non-dimensionalised with respect to the incident wave height and the pitch motion with respect to wave slope. The positive sign conventions used for heave and pitch throughout this project are as presented in Figure 2.3.

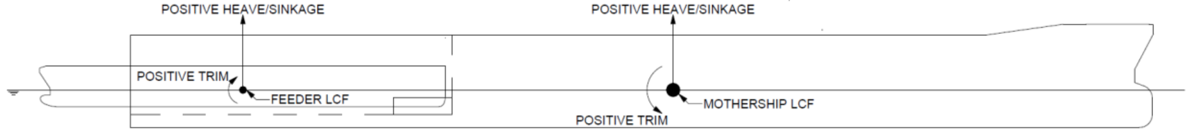

Figure 2.3: Positive sign convention for heave and pitch for both vessels used throughout this project.

In this section, results obtained from the various aspects of the seakeeping study are presented. Discussion arising from these results, and the implications on this transhipping concept, is provided in Section 2.4.

2.3.1 Comparison to open water motion response

The present study involves an additional feasibility check by comparing the motion response of the mothership and feeder vessel in the docked condition to the feeder vessel operating independently in open water. The feeder vessel was tested independently in pure following seas to permit a direct comparison against the feeder vessel when docked, stern first, inside the well dock. The motion response of the feeder vessel model at zero forward speed in following seas in open water was compared to the case where it was inside the well dock of the mothership, as shown in Figures 2.4 and 2.5.

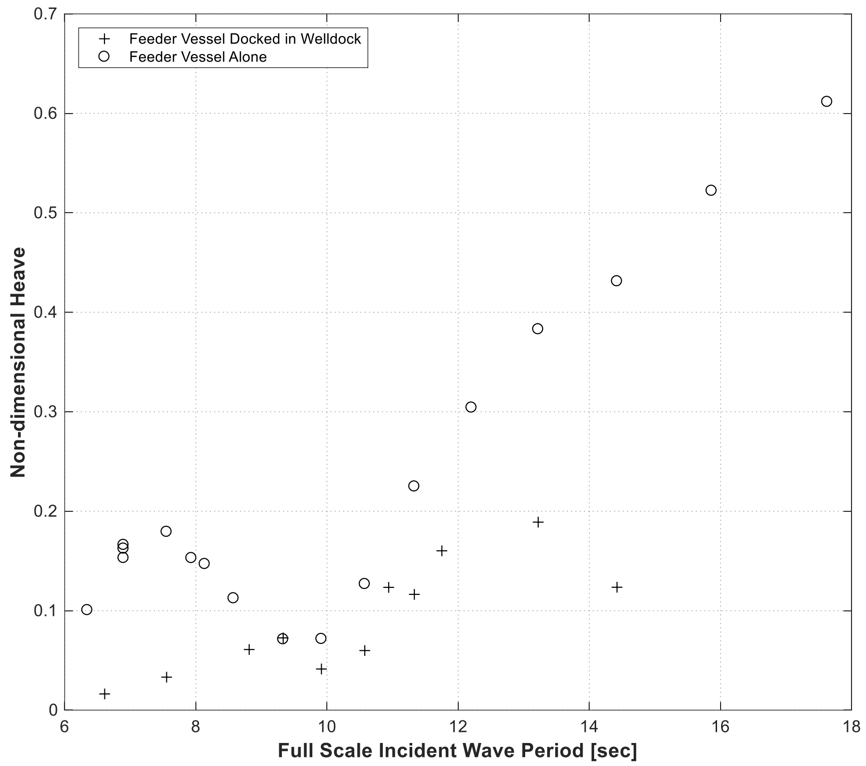

Figure 2.4: Feeder vessel heave motion non-dimensionalised with respect to incident wave height in following seas at zero forward speed for both the open water and docked scenarios.

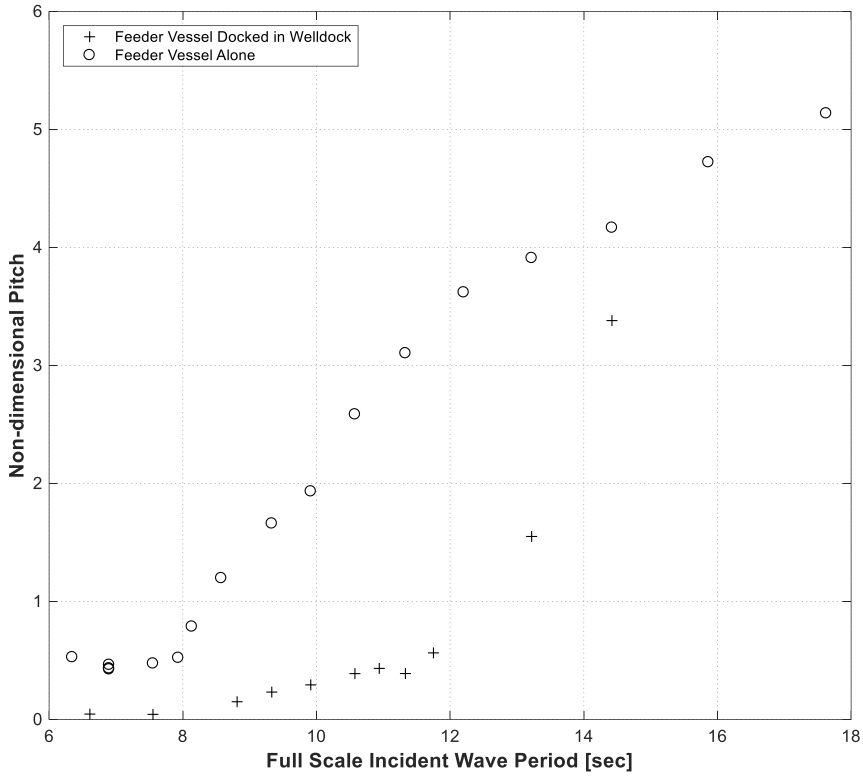

Figure 2.5: Feeder vessel pitch motion non-dimensionalised with respect to incident wave slope in following seas at zero forward speed for both the open water and docked scenarios

2.3.2 Effects of well dock vent size on energy within the well dock

As previously mentioned, one of the perceived benefits of docking the feeder vessel within the well dock is that the energy of the incident sea state is predominantly impinging upon the mothership from the bow due to the head seas orientation. As the feeder vessel is sheltered from this sea state by the mothership it is expected that there will be a significant reduction in wave energy transmitted to the environment within the well dock as compared to the far field region. To understand the effect that the well dock vent size has on the amount of wave energy being transmitted to the environment within the well dock, the energy spectrum of the sea state within the open well dock, without the feeder vessel present, was interrogated. The well dock wave power spectrum is presented in Figure 2.6 for a full scale incident wave period of 10 s and Figure 2.7 for a full scale incident wave period of 14 s. The full scale wave height was held constant at 4 m for both of these plots.

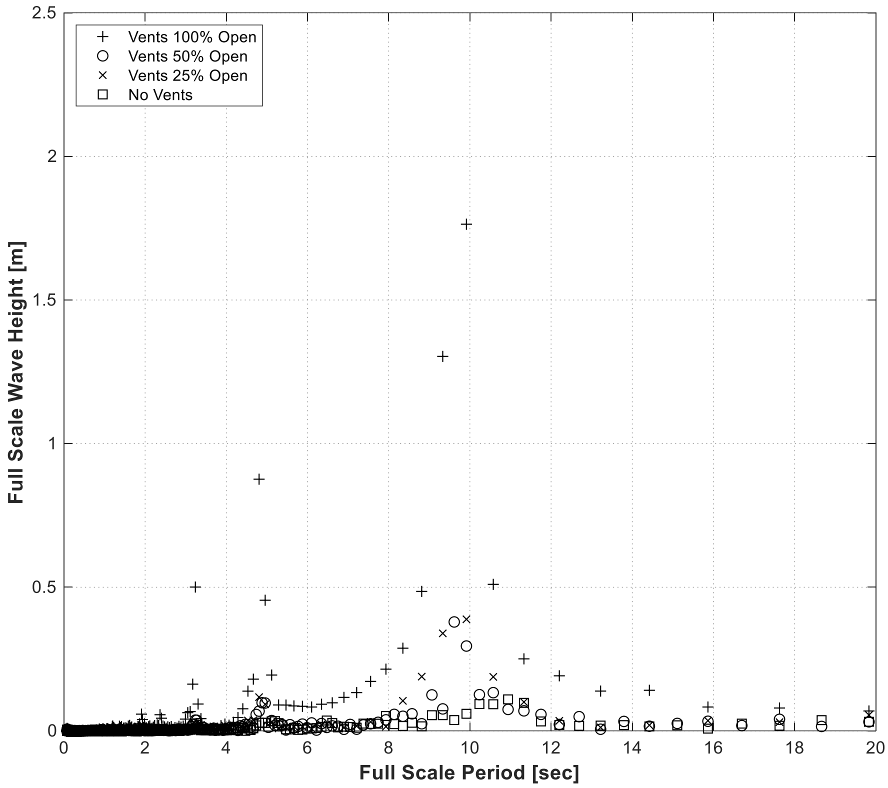

Figure 2.6: Open well dock wave environment power spectrum for a 10 s full scale incident wave period and 4 metre full scale wave height.

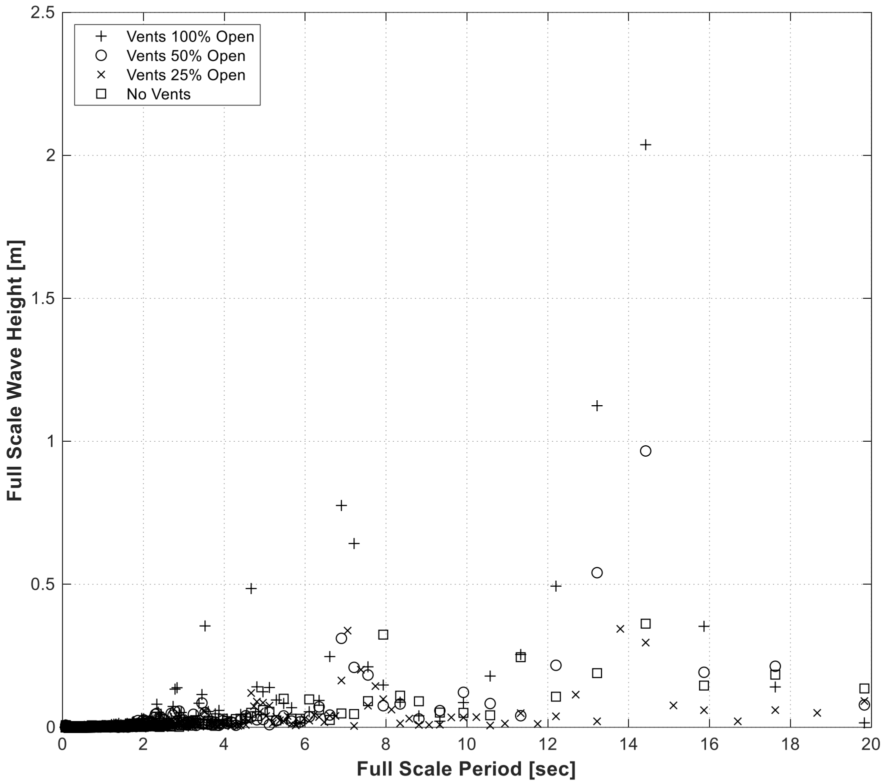

Figure 2.7: Open well dock wave environment power spectrum for a 14 s full scale incident wave period and 4 metre full scale wave height.

2.3.3 Effect of well dock vent size on vessel motions

It is hypothesised that the proposed vents may lead to a reduction in sheltering effect that the mothership has upon the feeder vessel because the artificial environment that exists within the well dock will be more influenced by the external sea state as there is extra permeable area for wave energy to enter the well dock. The effect of well dock vent size has been investigated by performing the docked seakeeping experiments for the four different vent configurations described in Section 3.1. The heave and pitch behaviour of both vessels have been analysed to identify any potential effects of the well dock vents on vessel motion.

The non-dimensional heave motion response of the mothership for all four vent configurations is presented in Figure 2.8. The pitch motion response of the mothership for the various vent configurations is presented in Figure 2.9. The heave motion response of the feeder vessel is presented in Figure 2.10 for the range of tested wave periods at each of the four vent configurations. Figure 2.11 shows the feeder vessel pitch motion for the four different vent sizes.

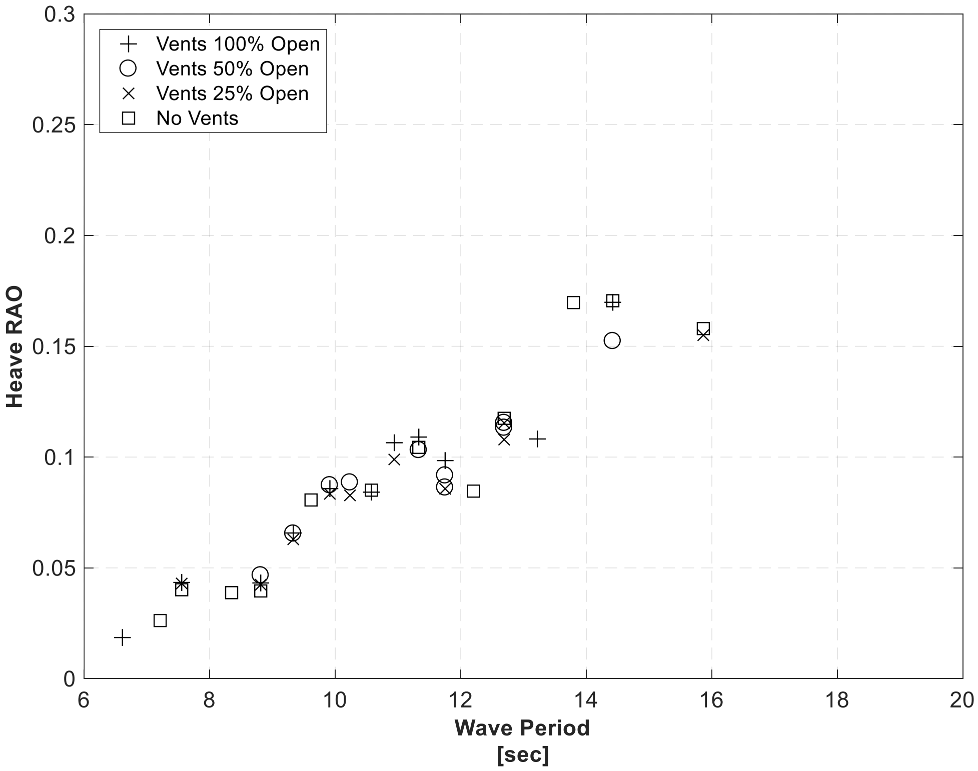

Figure 2.8: Mothership heave motion non-dimensionalised with respect to incident wave height in head seas at zero forward speed while the feeder vessel is docked for each of the four vent configurations.

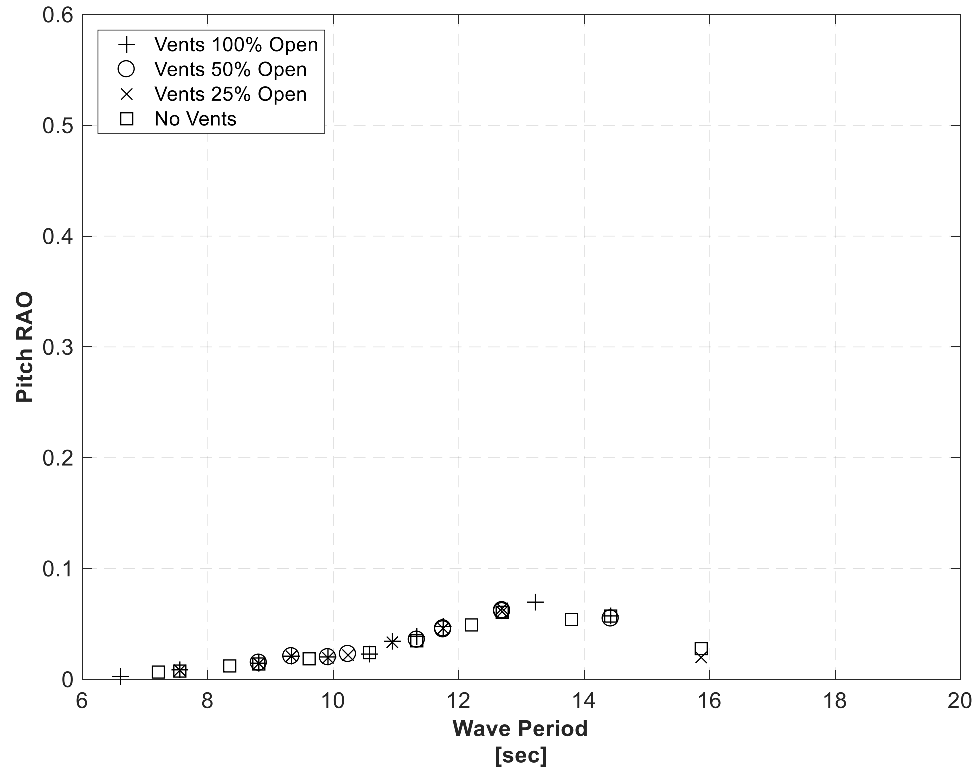

Figure 2.9: Mothership pitch motion non-dimensionalised with respect to incident wave slope in head seas at zero forward speed while the feeder vessel is docked for each of the four vent configurations.

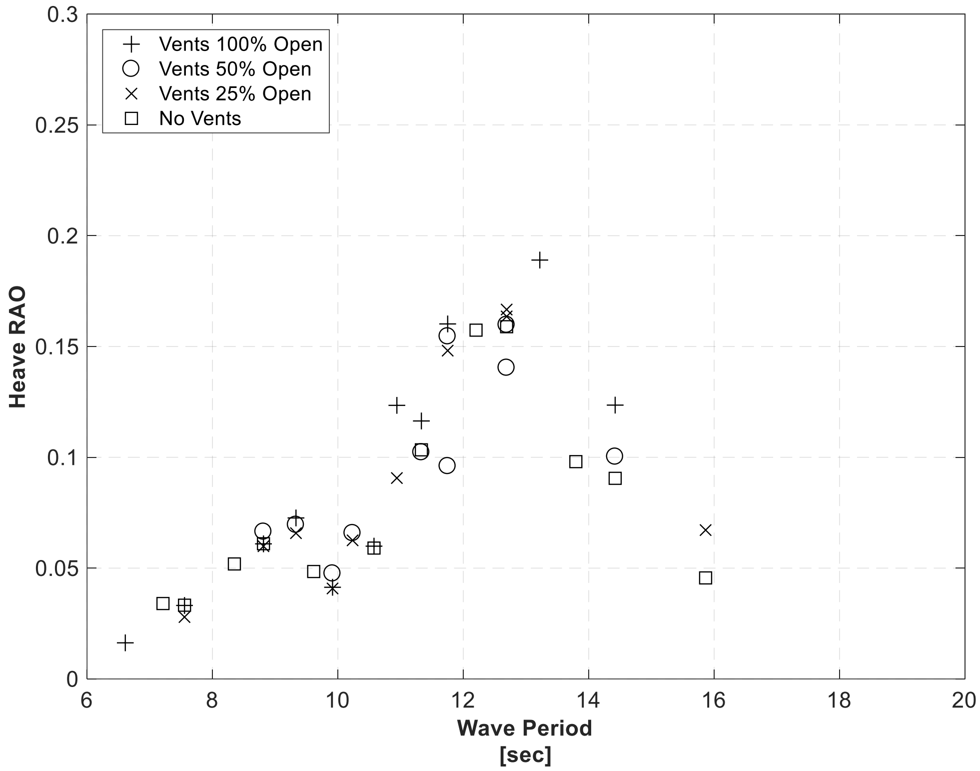

Figure 2.10: Feeder vessel heave motion non-dimensionalised with respect to incident wave height in following seas (relative to the feeder vessel) at zero forward speed while the feeder vessel is docked for each of the four vent configurations.

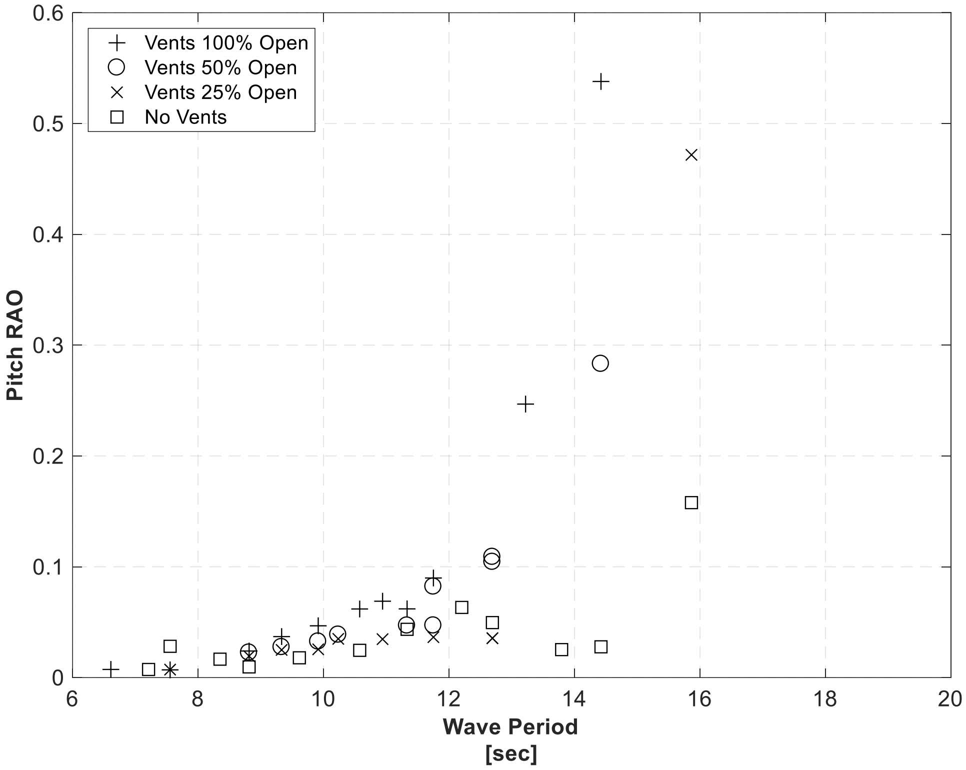

Figure 2.11: Feeder vessel pitch motion non-dimensionalised with respect to incident wave slope in following seas (relative to the feeder vessel) at zero forward speed while the feeder vessel is docked for each of the four vent configurations.

2.3.4 Relative motions between the vessels

Due to the operations-centred design drivers of the well dock concept, the most important motion behaviour is the relative motion between the docked feeder vessel and the mothership, in particular the under keel clearance between the feeder vessel and the floor of the well dock. This relative motion becomes very complicated especially in the likely scenario where a phase difference between the motions of the two vessels exists, which was observed during almost all tests conducted. In order to capture the effect of the phasing difference the motions of the two vessels must be considered in the time domain. Superimposing the time domain motions of each vessel allows metrics such as the under keel clearance between the two vessels at any point to be determined. It is important to quantify the minimum under keel clearance between the two vessels to identify the potential risk of impact between the two vessels, as this may result in significant damage and downtime as previously discussed.

The under keel clearance at any point between the two models is determined using the vessel motion data and simple geometry. As previously discussed, only the heave and pitch motions were deemed to be of interest for this investigation. This simplification led to the possible points of first contact between the vessels being reduced to only two locations; the aft-most point of the mothership and the aft-most point of the skeg of the feeder vessel, as indicated in Figure 2.12. With the absolute lowest under keel clearance being present at one of these two points at all times, the under keel clearance was determined for each of these locations at all time-steps allowing the change in minimum under keel clearance to be plotted against time.

All change in under keel clearance measurements are presented as a percentage of the static under keel clearance between the two vessels. This leads to a plot where a value of -100% indicates contact between the vessels and 0% indicates no departure from the static position.

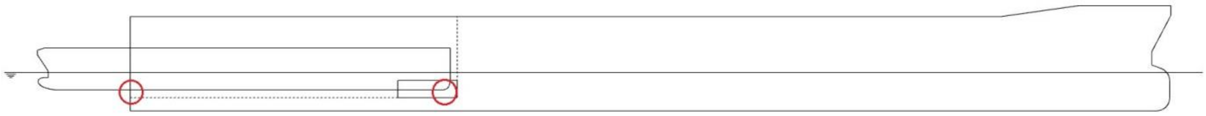

Figure 2.12: Side profile of the feeder vessel docked within the well dock highlighting the potential locations at which contact could occur between the vessels.

Two samples of minimum under keel clearance time series plots are provided in Figure 2.13 to highlight the significant difference between the vents 100% open and the no vents configurations. These plots were generated for an incident full scale wave period of 14 s at the 4 metre full scale wave height. These wave parameters were selected as this is a point at which there was found to be a significant effect of the well dock vent size on the minimum under keel clearance between the vessels. Figure 2.14 shows the change in under keel clearance between the feeder vessel and the well dock floor as a function of full scale incident wave period for each of the four vent configurations at the 4 metre full scale wave height. The minimum under keel clearance at any time during a run is compared to the static under keel clearance to identify the reduction in under keel clearance. The minimum under keel clearance for the 2 metre full scale wave height is presented in Figure 2.15.

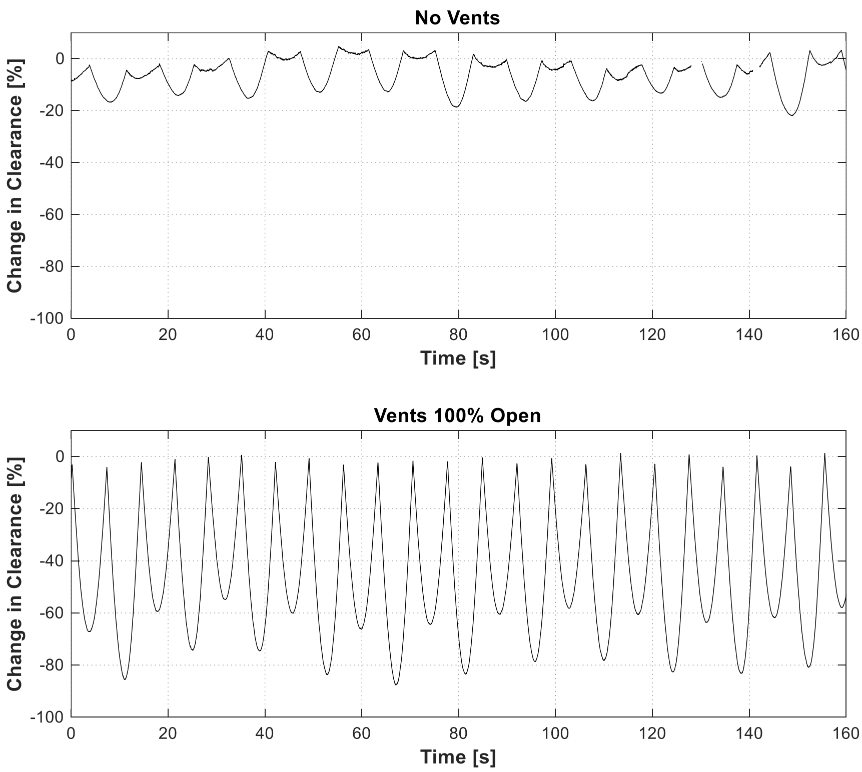

Figure 2.13: Change in minimum under keel clearance between the feeder vessel and mothership (as a percentage of static under keel clearance) for the no vents and the vents 100% open configurations, full scale incident wave period of 14 s and full scale wave height of 4 m.

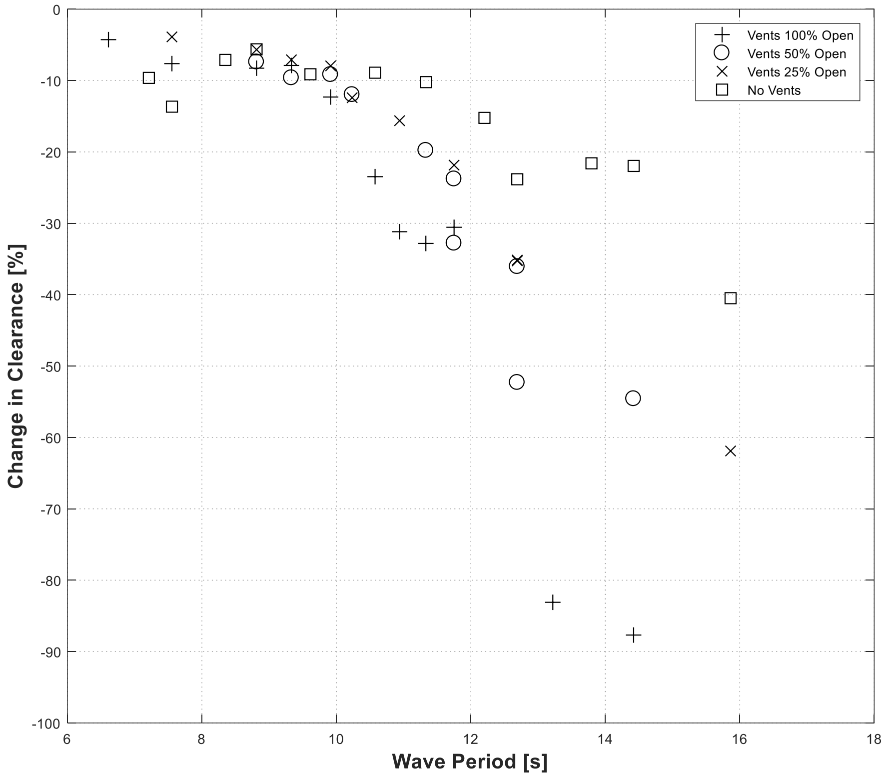

Figure 2.14: Change in minimum under keel clearance between the feeder vessel and mothership (as a percentage of static under keel clearance) for each of the vent configurations across the range of incident wave periods at the 4 metre full scale wave height.

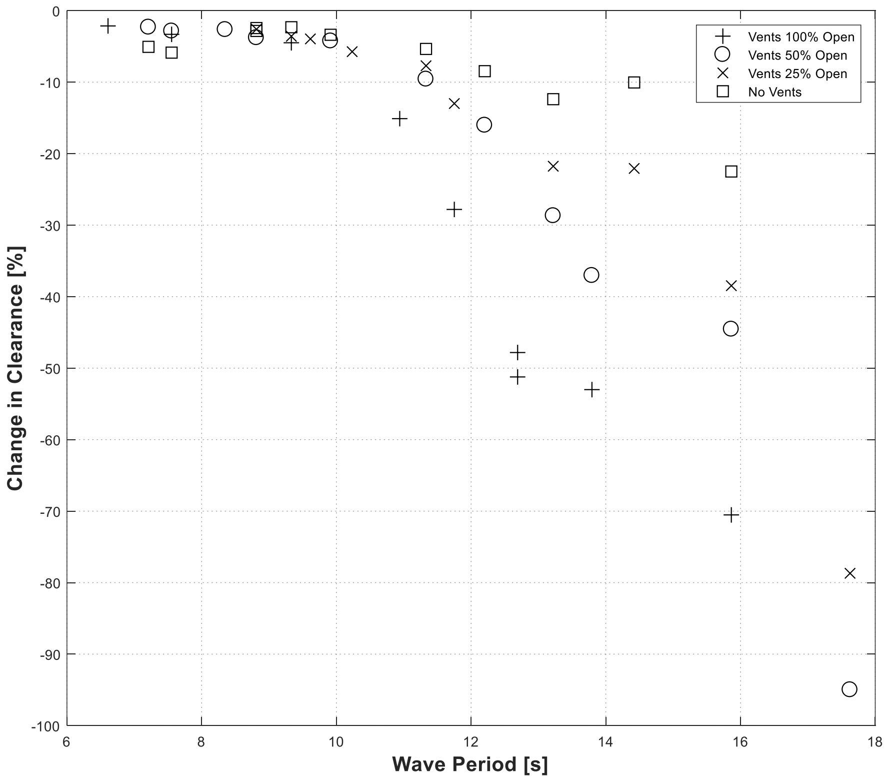

Figure 2.15: Change in minimum under keel clearance between the feeder vessel and mothership (as a percentage of static under keel clearance) for each of the vent configurations across the range of incident wave periods at the 2 metre full scale wave height.

2.4 Discussion

2.4.1 Comparison between open water, side-by-side and docked scenarios

It can be seen that both the heave (Figure 2.4) and pitch (Figure 2.5) motion response of the feeder vessel are significantly reduced at zero forward speed over a wide range of incident wave periods when the feeder vessel is docked within the mothership compared to the open water case. It was noted that the shorter period waves up to 12 s yield a large reduction in pitch motion when the feeder vessel is docked. When the feeder vessel is in open water a local maximum in heave is observed at 7.5 s. This was absent in the docked data set highlighting the sheltering of the well dock.

For the open water case, the non-dimensional heave generally increases (towards 1.0) with increasing wave period, as would be expected, however there is a lesser local peak around the lower periods of 7-8 s. This is followed by a minima at approximately 9 seconds where the open water case exhibits a heave amplitude equal to the feeder vessel when docked. This somewhat unusual local maxima is likely due to resonance when the incident wave frequency is close to the free damped natural heave period. This effect reduces as the incident wave period moves away from this period and returns to a smaller value as observed at 9 seconds.

When the feeder vessel is sheltered within the well dock, this resonant behaviour is not as obvious because the sheltering effect of the well dock reduces the amplitude of the incident sea state and may also alter the encounter frequency relative to the feeder vessel. At low periods the pitch motion is virtually non-existent and the heave motion at most periods is significantly reduced. For the non-dimensional pitch motions, a substantial reduction was observed when in the well dock at all but the highest wave period investigated (where there was still a 20% reduction). For periods in the mid-range of 9-12 s, this reduction often exceeds ~70%.

Also of relevance to this study are the motions of the feeder vessel inside the well dock directly compared against the more traditional transhipping technique where the feeder vessel is moored alongside an ocean going vessel. This comparison was performed by Macfarlane, et al. (2012) as part of the proof of concept study, where it was found that both the heave and pitch motions were considerably larger for the side-by-side case. Of significant concern were the notable pitch and roll motions of the feeder vessel when moored alongside, which were found to be almost an order of magnitude greater than the case when the feeder vessel was located inside the well dock. It was also noted that the presence of the feeder vessel alongside adversely affected the roll motions of the mothership for wave periods greater than 8 s.

In summary, the results from the two independent series of experiments that compared the feeder vessel motions when inside the well dock of the mothership against both the side-by-side and open water cases indicate that there is a potential reduction in feeder vessel motions when utilising the sheltered zone offered by the well dock. The present study also assessed the motion response behaviour of the mothership with and without the feeder vessel in the well dock. The results are not presented in this chapter because the comparison revealed that the presence of the feeder vessel in the well dock had negligible effect upon the mothership motion response. This finding supports those of Bass, et al. (2004) who found that the internal sea state within the well dock has little effect upon the motion response of amphibious vessels.

2.4.2 Energy transmission into the well dock

Further experiments were performed to quantify the altered wave environment inside the well dock without the feeder vessel present. By studying the time series data acquired from wave probes installed in the open well dock it was observed that the wave environment was highly irregular at most incident wave periods and vent configurations. This confirmed that the wave environment within the well dock was significantly different to the incident wave conditions. It is not known whether this knowledge has any direct relevance to the resultant motions experienced by the feeder vessel due to the large differences in scenarios (when docked, the feeder vessel displaces a large volume of water leaving only a small fraction of free surface), but it does help to understand the magnitude of wave energy that can be transmitted into the well dock via the open vents.

The significant wave height and modal frequency of the altered wave environment inside the well dock was interrogated and these parameters were found to have limited correlation with the four different vent conditions investigated. However, the power spectrum was then investigated and revealed a significant correlation between the wave energy transmitted into the well dock and vent size. Energy transmitted to the well dock increases as the vent area becomes larger, as seen in Figure 2.6, where the power spectrum for the wave environment within the well dock for each of the four vent configurations are plotted for a 4 metre high, 10 s period regular incident wave. It can be seen that the vents 100% open case has a much greater area under the power spectrum than any of the other configurations where vent size has been reduced. For the fully open vent case there are also two additional peaks present at lower wave periods that are barely visible at the lesser vent sizes. Across all four vent configurations there was a clear peak at a period of approximately 10 s which indicates that the modal frequency of the well dock wave environment is equal to the regular wave that the whole system is being subjected to. It is interesting to note that the vents 50% and 25% open cases exhibit similar maximum measured values, with the vents 50% open configuration yielding a broader peak. The no vents configuration demonstrated a very supressed peak indicating that a significant amount of wave energy is blocked from entering the well dock.

Similarly, the power spectra within the well dock for each of the four vent conditions are shown in Figure 2.7, but in this case for a longer (14 s full scale) incident regular wave. Many of the same trends seen at the 10 s wave period are again present, however the longer period wave leads to a much broader peak at 7 s, which is the first harmonic of the incident wave. Unlike the 10 s incident wave case, this peak is visible across all four vent configurations with the vents 50% open and vents 25% open cases having a similar local maximum measured power spectrum ordinate magnitude and period. The no vents configuration demonstrated a similar maximum power spectrum ordinate but at a slightly higher period. This suggests that the no vents configuration was slowing the transmission of energy into the well dock. The maximum measured energy was once again found to occur at approximately the incident wave period. However, unlike the 10 s incident wave period results, there is a discernible difference between the 25% open vents and the 50% open vents configurations. Again, a clear trend was evident that reduction in the vent size reduced both the magnitude and breadth of the peak, but for the 14 s period incident wave, this peak was seen to occur at a slightly higher period as the vent size was reduced.

These factors indicate that, not surprisingly, there is more energy transmitted into the well dock at the 14 s than the 10 s incident wave period, but interestingly there is a greater variation in the amount of energy transmitted between the four vent configurations at the longer 14 s incident wave condition. The incident wave field for these comparisons were also analysed using the same method, this showed that the magnitude of the peaks were quite similar to the 100% open vents configuration but were wider inside the well dock. This indicates that the vents 100% open configuration allows nearly all of the wave energy to be transmitted into the well dock.

While these two incident wave frequencies were selected to investigate the potential causes for the variation in feeder vessel motions, a similar trend of decreased energy in the well dock for decreased well dock vent area was observed throughout the range of tested wave frequencies. The feeder vessel free damped periods in both pitch and heave were determined and were found to be at much lower periods than any of the significant data points on either of the power spectra. This indicates that there is not likely to be any resonance contributing to the feeder vessel motions at any vent condition across the range of incident wave periods investigated.

2.4.3 Effect of the well dock vent size on vessel motions

It has been shown that the well dock vent size has an effect on the amount of energy in the open well dock wave environment when the feeder vessel is not in the well dock. However, the effect that the feeder vessel may have on these phenomena is unknown. Based on the results from the tests undertaken without the feeder vessel present in the well dock, it is expected that the feeder vessel motion response will be more favourable when the vent area is reduced. However, it is unknown what effect the vent configuration may have on the motion response of the mothership and further what effect this might have on the relative motions between the two vessels.

The mothership motion response was measured for the four vent configurations across the range of tested incident wave periods with the feeder vessel docked. Both heave (Figure 2.8) and pitch (Figure 2.9) motion response show no conclusive effect of the vent configuration on the motion response of the mothership across most of the range of full scale incident wave periods, both in terms of magnitude or location of maximum measured motion. There is a variation in the pitch motion at a full scale incident wave period of 16 s and repeatability of other data points indicates that at this wave period there is a reduction in mothership pitch as the vent size is increased. This indicates that, at all wave periods other than the longest investigated, any effect seen within the wave environment or feeder vessel motion due to variation in vent size is not attributed to a variation in mothership motion.

This shows that there is no clear effect of the vent size on the heave motion response of the feeder vessel while it is docked within the mothership. There is however a general trend visible that the largest vent leads to larger heave motion and shows a clear difference between the four vent configurations, particularly at the longer incident wave periods.

Feeder vessel heave motion (Figure 2.10) shows that there is slightly more effect of the vent size on the feeder vessel heave than on the mothership motions, however there is no clear correlation between the vent size and the heave motion of the feeder vessel across the tested incident wave periods. The data points exhibit a slight variation with respect to the vent size and the repeat points show close matches indicating that at incident full scale wave periods longer than 11 s the vents 100% open condition leads to greater feeder vessel heave motion while the remaining three configurations don't show an effect until incident wave periods of greater than 14 s.

Unlike the heave motion, there is a very marked effect on the pitch response of the feeder vessel with variation in vent size (Figure 2.11). There is minimal discernible variation in the feeder vessel pitch motion at full scale incident wave periods of 10 s and below, however for longer periods there begins to be significant variation between the vent configurations. The wave period at which the pitch motion starts to rapidly increase is different for each of the vent configurations: the more open the vent configuration the lower the wave period this occurs. For example, with the vents open 100% the pitch response starts to rapidly increase as wave period increases above 11.5 s, this shifts to 12.5 s at 50% open, and 14.5 s when there are no vents. It is worth noting that once the pitch motion begins to increase, there is no peak present within the data, which indicates that the motion became too large for the experiment before a peak response was reached. These results indicate a clear effect of the vent configuration on the feeder vessel pitch motion with a correlation between increased vent area and increased pitch motion.

2.4.4 Effect of well dock vent size on relative motions

The most important factor from an operational point of view for the well dock concept is the under keel clearance between the underside of the feeder vessel and the floor of the well dock. The minimum under keel clearance is a function of both vessels' heave and pitch motion at any point in time.

The time series of the minimum under keel clearance for the no vents (Figure 2.13, top) and the 100% open vents (Figure 2.13, bottom) configurations for an identical full scale incident wave condition (4 m high, 14 s period). These plots show the minimum distance between any two points of the two vessels at each time step. They also demonstrate significant differences in motion response between the vents 100% open and the no vents configurations. In particular the 100% open vent condition has a much greater amplitude of oscillation while the no vents condition exhibits very little relative motion between the vessels. The behaviour displayed in both plots is seen to repeat in pairs of peaks, this is due to the plot presenting the minimum under keel clearance present at any point in time and every two peaks represent one full cycle of vessel motions. The very flat nature of every second peak observed within the no vents condition plot is due to the two vessels moving in phase at one end of the feeder vessel and moving almost exactly out of phase at the other end of the feeder vessel because both points are aft of amidships for the mothership while one is forward and one is aft of amidships for the feeder vessel. This same behaviour occurs when the well dock vents are in the 100% open configuration, however the feeder vessel motion significantly dwarfs the mothership motion.

The overall minimum under keel clearance at any time throughout the time series was identified for each run and plotted against the full scale incident wave period for each of the vent configurations (Figure 2.14). This plot presents runs conducted at a full scale wave height of 4 m and gives an overview of the most important factor of the under keel clearance behaviour for each run. This information quite clearly demonstrates that vent configuration has minimal effect for wave periods below about 10 s, but as wave period increases beyond 10 s a reduction in vent size is particularly beneficial. There is a very strong correlation shown between the increase in vent size and the minimum under keel clearance. There are several data points missing from the longer wave period region for the 100% open vent condition as these were unable to be consistently analysed due to contact between the models, highlighting the significant increase in relative motions in this scenario. Figure 2.15 presents the results for the smaller incident wave height of 2 m full scale, however a more complete dataset is available due to the reduced motions (no impacts between the two models was observed). These plots clearly demonstrate that there is a strong correlation between an increase in the vent size and the minimum under keel clearance.

2.5 Summary and broader implications

The introduction of the 100% open vents in the well dock of the mothership has been demonstrated to (a) increase the wave energy in the open well dock; (b) significantly increase the feeder vessel pitch motions, and (c) significantly reduce the under keel clearance between the feeder vessel and well dock floor, when compared to a well dock with no vents. Interrogation of two intermediate vent sizes revealed behaviour midway between the vents 100% open and no vents configurations. This demonstrates that from a purely seakeeping point of view there are clear benefits to reducing the vent size and maybe even avoiding them all together if possible. However, none of the conditions investigated thus far have addressed the reason that the vents were considered in the first place: the docking process of the feeder vessel into the well dock, when a large volume of water must be displaced (this is addressed in Chapter 3). It is hypothesised that increased vent size will yield more favourable docking performance and thus there will likely need to be a compromise required during the design process as to the most appropriate vent configuration. The potentially adverse effects on seakeeping performance is a disadvantage of including vents in the well dock but there is also a structural disadvantage of including vents through the side of the mothership, which highlights the importance of understanding the effect of vent size.

The uncertainty within of measured results is addressed in greater detail within the Appendix. In cases where the magnitude of the measured parameter is small and the behaviour between different conditions is similar, it is difficult to draw clear conclusions.

The proof of concept study by Macfarlane, et al. (2012) did not investigate the effect that the well dock has on the seakeeping performance of the mothership. If the inclusion of a well dock were to dramatically reduce the seakeeping abilities of the mothership then that would need to be considered during other comparisons.

To identify the effect of the flooded well dock on the seakeeping performance of the mothership a related project was undertaken (by an engineering Honours student under the supervision of the project team) (Atkinson, 2016). This experimental investigation compared the seakeeping performance of the mothership with and without the well dock. Tests were conducted in regular sea states over a range of wave periods and heights. Both the pitch and heave motion were found to be quite linear with respect to wave height so the 4m full scale wave height was chosen to demonstrate the effect of the well dock on the heave and pitch of the mothership. The motion response data was non-dimensionalised in the same manner used for the docked seakeeping investigation.

The non-dimensional heave response of the mothership with and without the well dock is presented in Figure 2.16 and demonstrates that the well dock has a negligible effect. The non-dimensional pitch response (Figure 2.17) shows an even more consistent response between the well dock and without well dock configurations. This trend was consistent across the tested configurations and confirms that the well dock has no significant effect on the seakeeping performance of the mothership.

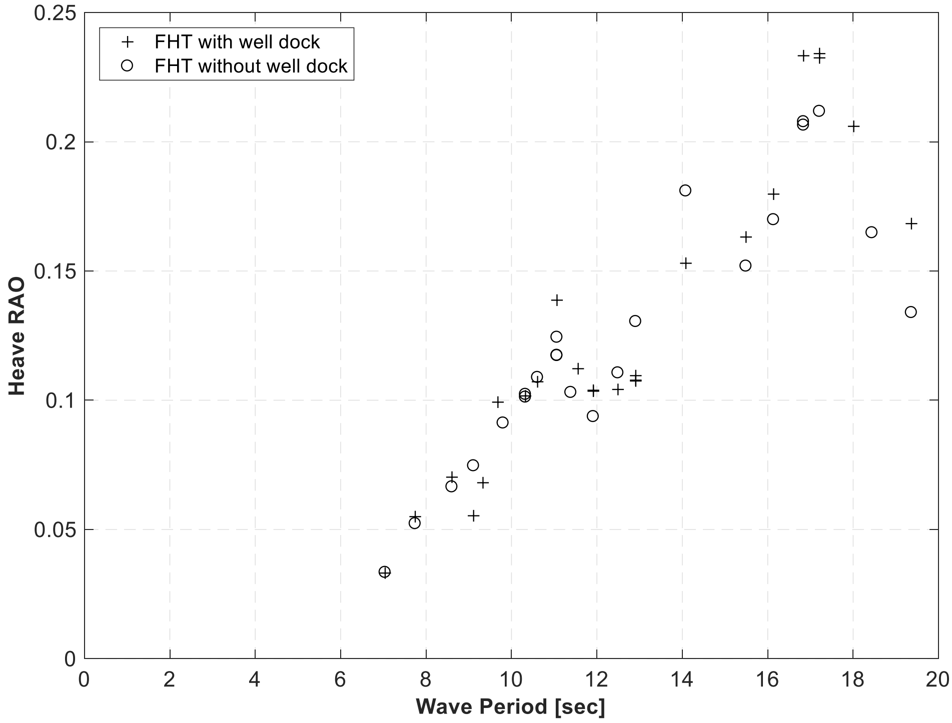

Figure 2.16: Mothership heave motion non-dimensionalised with respect to wave height in head seas at zero forward speed for the mothership with and without a well dock.

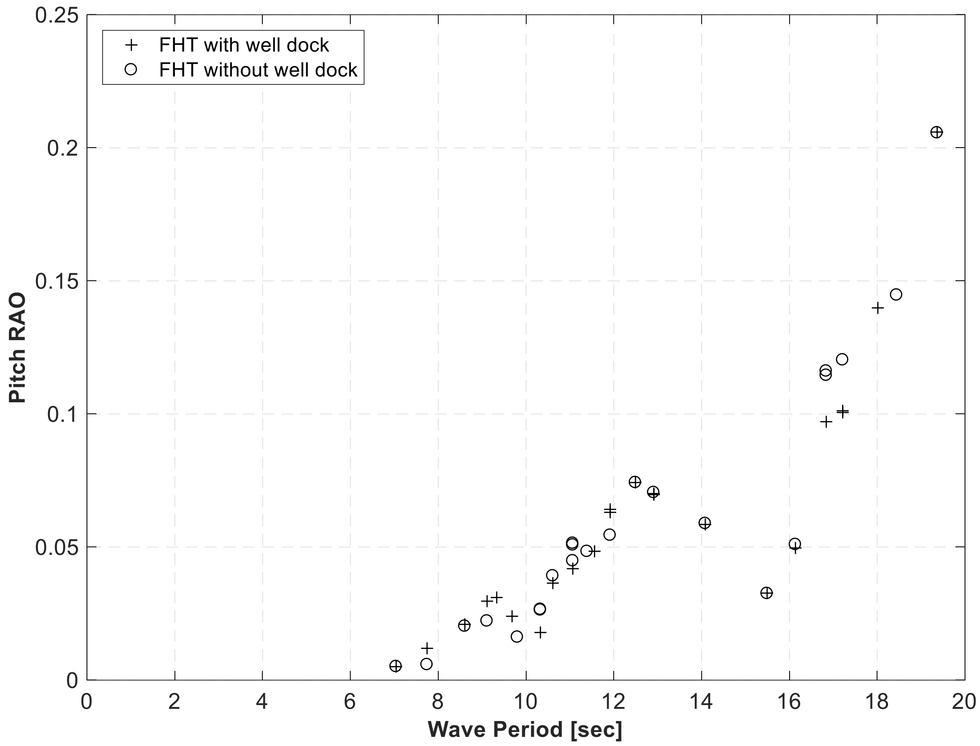

Figure 2.17: Mothership pitch motion non-dimensionalised with respect to wave slope in head seas at zero forward speed for the mothership with and without a well dock.

Another aspect that deserves investigation and quantification is the sheltering effect that the mothership creates close to its transom. Logic states that there is likely to be a sheltered region aft of the mothership when it is subjected to head seas and the intention is to leverage this to make the feeder vessel docking process easier. A related project was undertaken (by an engineering Honours student) to quantify the sheltered region aft of the mothership when subjected to head seas using scale model testing (Wight, 2016). This experimental program investigated the effect of wave period on the size of the sheltered zone by measuring the wave height at numerous locations aft of the mothership (without the feeder vessel in the well dock). This measurement was non-dimensionalised with respect to the incident wave height such that no sheltering effect is represented as a value of 1.0 and completely still water in the sheltered region is represented by a zero value.

A sample of the results are presented in Figure 2.18 for a position on the mothership centreline 75 m full scale aft of its transom. It is clear that the mothership provides a significant sheltering effect for short period waves and, in general, this reduces with increasing wave period. The results at two incident wave periods (11.1 and 14.1 s) did not follow the trend displayed by similar wave periods. The level of sheltering rapidly reduces as incident wave period increases above approximately 14 s while for very short wave periods (less than approximately 8 s) the mothership is very effective at providing a sheltered zone. Between 8 and 14 s approximately 50% reduction in wave height was observed (excluding the outlier at 11.1 s).

This region of mid-range wave periods was investigated further to identify the effect of transverse position on the sheltering effect (at the same distance aft of the mothership transom), as seen in Figure 2.19. The sheltering effect was found to be reasonably consistent across the width tested (approximately 50m either side of the centreline) for wave periods of 10.3 and 12.9 s. Interestingly, at the incident wave period that corresponds with the most obvious outlier in Figure 2.18 (11.1 s) the reduction in wave height is least pronounced at the mothership centreline, but the sheltering effect improves away from the centreline (to around 50% reduction, as found at similar wave periods). These results indicate that the height of the waves within the shelter zone aft of the mothership is significantly dependant on wave period and can be complex. It is possible that the increase in height around the centreline of the ship at very specific wave periods is influenced by a wave exiting the well dock, which may warrant further investigation.

However, this preliminary investigation has confirmed that the presence of the mothership clearly provides a sheltered region around the entrance to the well dock, which should benefit feeder vessel manoeuvres in or out of the well dock. The level of wave height reduction is significant, approximately 50% or greater, for much of the range of wave periods of interest.

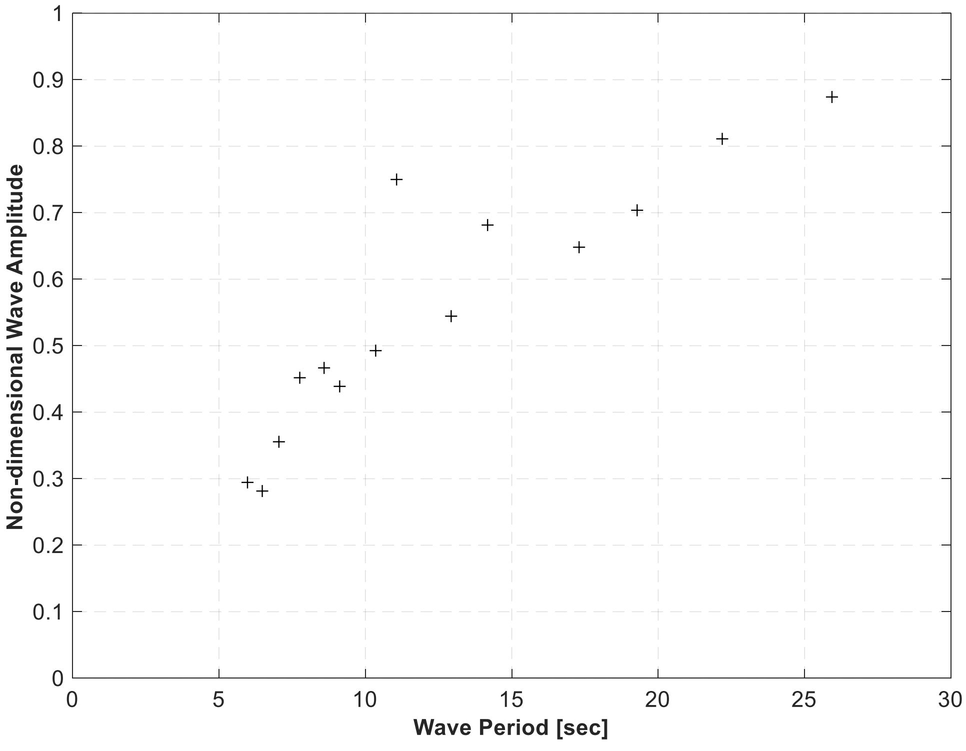

Figure 2.18: Non-dimensional wave height measured 75 m (full scale) aft of the mothership in line with the centreline of the vessel plotted against the wave period.

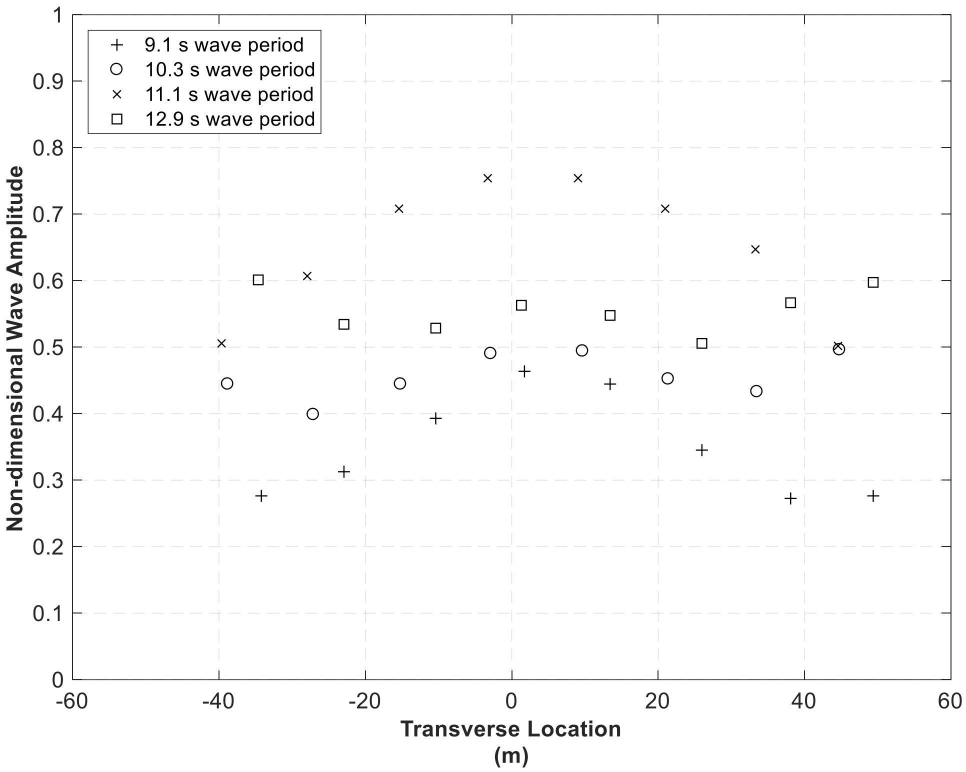

Figure 2.19: Non-dimensional wave height measured 75 m (full scale) aft of the mothership plotted against the transverse location relative to the centreline of the vessel.

2.6 Concluding remarks

The concept of a well dock to facilitate the loading and unloading of feeder vessels that cause significant blockage within the well dock are to this point very new and uncharted territory in the field of transhipping. This concept presents many unique hydrodynamic considerations that must be better understood to draw the most from the well dock concept. The seakeeping performance of a feeder vessel and mothership while the feeder vessel is docked has been explored with an emphasis placed on the relative motion between the two vessels as this will be a critical parameter when a feeder vessel is operating within the well dock.

This investigation has shown that the motion response of the feeder vessel is significantly more favourable when docked within the well dock compared to open water. This supports previous studies which confirmed the application of a well dock provides shelter leading to more favourable seakeeping performance for the docked feeder vessel than the traditional side-by-side transhipment in sea states up to 4 m, thus greatly increasing the potential weather window for operations.

The effect of the well dock vents on the altered seaway within the well dock was investigated by measuring the free surface within the well dock while the feeder vessel was not present. This showed that while there was no clear correlation between the well dock vent size and the significant wave height or modal period within the well dock, there was a strong correlation between the wave energy within the well dock and vent size. It was found that a larger vent size yielded significantly more energy being transmitted into the well dock and this effect was shown to be more significant at a full scale incident wave period of 14 s than at 10 s.

It was shown that the inclusion of vents, regardless of size, had a very limited effect upon the seakeeping performance of the mothership. It was found that there was a loose correlation between the vent size and the heave motion response of the feeder vessel with the largest vent size exhibiting the largest heave response at longer incident wave periods. The most significant impact of the well dock vent size was observed within the feeder vessel pitch motion response: as vent size increased, the pitch motion response increased and the incident wave period at which the pitch motion was excited became lower.

From an operational point of view the relative motion between the feeder vessel and the mothership is very important due to the ship-to-ship material transfer methods intended. This was investigated by tracking the under keel clearance in the time domain where the effect of the vent size was seen to be quite marked, with the increased feeder vessel pitch being a strong influencing factor. An increase in the well dock vent size was conclusively shown to yield a much larger relative motion between the two vessels leading to a much greater reduction in under keel clearance at both the 2 and 4 m full scale incident wave heights.

It can be clearly concluded that there are significant penalties to the docked seakeeping performance of the feeder vessel, and by extension the well dock concept, for transhipping when high levels of fluid ventilation is present within the forward end of the well dock. This highlights that well dock vent size should be optimised when possible for the application of well dock based transhipping occurring in open seaways. It is however acknowledged that the present experimental investigation considers only the scenario when the feeder vessel is docked: Chapter 3 considers the scenario whereby the feeder vessel enters and exits the well dock, which is where it is anticipated the well dock vents will provide measureable benefits. It is likely that a compromise in vent size may be required between the docked seakeeping performance and the docking performance of the feeder vessel.

CHAPTER 3

Docking a Feeder Vessel inside the Well Dock of a Mothership

3.1 Introduction

This chapter discusses the hydrodynamics for a unique scenario: the tightly confined space in between the feeder vessel and the well dock. This results from the large cross sectional area of the feeder vessel relative to the well dock dimensions, causing a large blockage. A large body of water has to be displaced when the feeder vessel enters the well dock. This water has to exit the well dock in the limited space between the feeder vessel and the well dock floor and side walls as highlighted in Figures 1.4 and 1.5. This restriction creates a significant flow of water in the opposite direction to the feeder vessel motion imparting a significant effect on the manoeuvring and propulsion characteristics of the feeder vessel. The result is a very complex and unusual scenario where several potential issues may arise that the Master of the feeder vessel must be able to safely manage, such as grounding, impact or uncontrollable surge motions.

The aim of the investigation presented in this chapter is to explore the docking behaviour of the feeder vessel. As was the case in Chapter 2, physical scale model experiments have been employed to achieve this, however in this case the longitudinal force, sinkage and trim characteristics of a feeder vessel while entering and departing from a well dock in calm water have been quantified and discussed.

3.2 Physical experiments

Physical scale model experiments have been employed throughout this investigation because of the unique and confined fluid flow expected. While numerical methods are becoming more successful in confined water situations with the incorporation of lid methods within potential flow solvers (Chen, 2005), the complicated and novel nature of the current research would require suitable experimental results in which to validate any and each numerical technique adopted. Experimental methods were employed in Chapter 2 of this study to investigate the docked seakeeping performance of the mothership and the feeder vessel and Chapter 4 adopts laser diagnostic techniques to experimentally explore the fluid flow inside the well dock as the feeder vessel enters/exits.

3.2.1 Facility and apparatus

Experimental testing was performed using 1:60 scale models of a feeder vessel and mothership in the finite water wave basin at the Australian Maritime College (AMC). The same load conditions used during the docked seakeeping study were adopted, simulating a fully loaded feeder vessel and lightly loaded mothership. It is acknowledged that it is unlikely the feeder vessel will both enter and exit the mothership well dock at the same (full) load condition, with the more likely scenario that one of the cases would be the feeder vessel empty condition. However, this choice of conditions provides a worst-case scenario in terms of under keel clearance as this accentuates the variation between vent conditions.

Unlike the docked seakeeping test, which considered various incident wave conditions, for this first experimental investigation into the docking of the feeder vessel, only calm water conditions have been considered. To focus on just the primary variables of interest, the model of the mothership was rigidly fixed in all six degrees of freedom. This is considered an acceptable assumption as the motions of the mothership were measured during the docked seakeeping experiments and found to be almost negligible for most wave frequencies at a regular wave height of two m. The model of the feeder vessel was constrained in surge, sway and yaw, while free to heave, pitch and roll. It was connected to an overhead carriage which provided the means to tow it in and out of the well dock in a controlled manner. No propulsors were fitted to the model of the feeder vessel. The effect of the confined water environment on the propulsors and vice versa was outside the scope of this investigation due to the already complex nature of the flow within the well dock.

A key component of the mothership model is the ability to vary the vent sizing between the following four different scenarios previously discussed: 100% open, 50% open, 25% open and no vents.

A plan view schematic (Figure 3.1) of the experimental apparatus shows the path of travel while moving astern to dock inside the mothership and Figure 3.2 shows a photograph of the feeder vessel attached to the tow rig. The towed path is approximately 4.3 feeder vessel lengths and allows for any ramp up effects to be stabilised before the feeder vessel nears the mothership. The feeder vessel is attached to the towing carriage via fore and aft tow posts, each of which include a 6DOF load cell to measure forces in the x (longitudinal) direction. Any vertical displacement experienced by feeder vessel, such as sinkage and trim, is measured by linear variable differential transducers (LVDTs) located at both the fore and aft tow posts. The longitudinal position of the feeder vessel is tracked using a Qualisys digital video motion measurement system. A rotary encoder mounted to the towing carriage drive motor directly provided the docking speed.

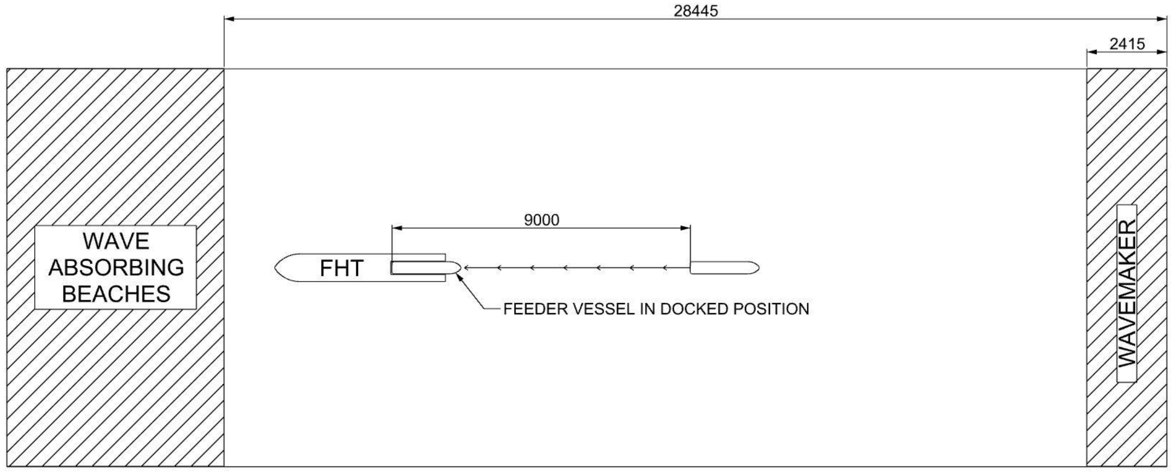

Figure 3.1: Plan view of the physical scale model setup in the finite water wave basin showing feeder vessel at the outermost position and the docked position. All dimensions are in millimetres.

Figure 3.2: A photograph of the experimental rig showing the feeder vessel about to enter the mothership well dock, stern first.

3.2.2 Scope of investigation

The scope of this experiment focussed on the measurement of specific parameters that were expected to demonstrate the effects of the well dock vents. The parameters selected for measurement were the longitudinal (drag) force on the feeder vessel and the trim and sinkage motions of the feeder vessel. These parameters highlight the confined water effects that the well dock vents are intended to mitigate. The feeder vessel longitudinal position relative to the mothership well dock was also recorded to enable measurements to be analysed in the position domain of the feeder vessel.

The testing matrix for this experiment had the potential to become very large due to the high number of independent variables involved. For this first-of-kind investigation, all testing was carried out in calm water to keep complexity to a manageable level and only one combination of vessel loading conditions was investigated (the 'worst' case as defined in Chapter 2). The scope of testing also covered the same four vent configurations as per the docked seakeeping study.

All test scenarios were conducted in both directions whereby the feeder vessel was moving astern in the inbound (docking) manoeuvre and moving ahead in the outbound (departing) manoeuvre. Following consultation with several ship Masters, the range of full scale vessel speeds that was deemed practical for these manoeuvres ranged from one to three knots (all references to vessel speeds are in full scale). The vast majority of model tests performed fell within this range, although some additional speeds – both higher and lower – were included to provide a broader understanding of the effect of speed. In this context, "speed" refers to the steady-state stage of the manoeuvre: for example, an inbound run at three knots indicates that the feeder vessel entered the well dock at a steady speed of three knots, prior to decelerating to a stop at the prescribed "docked" location.

The ramp rate of the feeder vessel was held at a constant linear value for all tests and was the same for both acceleration and deceleration of the feeder vessel. The distance required to decelerate from, or accelerate to, the two knot speed was set to approximately 58% of the length of the well dock. The feeder vessel was considered to be in the "docked" position when its transom was 35 mm at model scale (2100 mm full scale) from the end wall of the well dock. This consistency in both the docked position and the ramp rates allowed the feeder vessel measurements to be interrogated over a reliable and consistent window of steady speed data that was the same for every speed in both directions. This ensured that any variation observed between speeds or vent configuration was indeed a product of that independent variable rather than an effect from analysing a slightly different portion of the position domain data.

In order to gain a basic understanding of the effect that the significant depth and width constrictions of the mothership well dock has on the feeder vessel performance, it is useful to first compare this against results for the same feeder vessel operating in fully open water. Such open water experiments were performed in two facilities, each with a different water depth. In both test series the model of the feeder vessel was towed astern, simulating the case where it enters the well dock, and forward, for the departure case. The first series was performed in the finite water depth basin at the same time as the docking experiments, but well clear of the mothership. The non-dimensional water depth to draught ratio of the feeder vessel was 3.8, which is marginally below the ITTC guideline for deep water (ITTC, 2017). It was assumed that any shallow water effects should be negligible.

A second series of open water tests were performed in the 100 m long AMC towing tank, here the non-dimensional water depth to draught ratio was 17.2, which represents infinite depth. The open water data from the two facilities were compared, confirming there was no measurable finite water depth effects on the data acquired in the finite water basin (where the docking experiments were conducted).

3.3 Results

As previously noted, the measurements presented in this chapter are the longitudinal force, trim and sinkage of the feeder vessel. The origin for the sinkage and trim is the longitudinal centre of gravity (LCG). As will be seen, each of these three parameters often show similar trends for a given change in independent variable, which is believed to be because they are all drawn from the same fundamental phenomena of increased water flow along the hull.

When investigating the well dock concept for transhipment operations there are two initial considerations with respect to confined water effects: what is the effect of this unique confined water scenario when the feeder vessel enters or exits the mothership well dock; and to what extent does the introduction of well dock vents move to mitigate these effects? The overall effect of the well dock on the docking performance of the feeder vessel can be determined by contrasting the performance of the feeder vessel moving through open water against the case when the feeder vessel is entering or exiting the well dock. This enables the effect of the well dock vent size to be investigated by comparing the datasets obtained while the feeder vessel is moving through the well dock for each of the four vent configurations.

The results presented are non-dimensionalised to better serve the generalised discussion on the topic of a vessel operating within a (heavily constricted) well dock. The longitudinal force is non-dimensionalised with respect to the feeder vessel steady-state speed, feeder vessel length and water density according to Equation 3.1. The trim and sinkage are both non-dimensionalised with respect to the static under keel clearance as described in Equations 3.2 and 3.3. The static under keel clearance is the distance between the static feeder vessel and the well dock floor (see Figure 1.4). This was found to yield a very useful and informative measure as it describes how much the under keel clearance is reduced by the sinkage or trim in isolation. The trim was analysed between perpendiculars and a factor of a half was used such that contact between the vessels due to trim alone would be indicated by a non-dimensional trim value of one. A non-dimensional sinkage value of negative one indicates contact between vessels due to sinkage in isolation. A positive sinkage value indicates a bodily rise of the vessel while a positive trim value represents a stern down trim.

$$\mathrm{F}_{ND-x} = \frac{F_x}{\frac{1}{2} \times \rho \times v^2 \times L^2} \tag{3.1}$$

$$z_{ND-LCB} = \frac{z_{LCB}}{UKC_s} \tag{3.2}$$

$$t_{ND} = \frac{t}{2 \times UKC_s} \tag{3.3}$$

Where;

F_x	= Longitudinal force on feeder vessel
F_{ND-x}	= Non-dimensional longitudinal force on feeder vessel
ρ	= Water density
v	= Vessel speed
L	= Length between perpendiculars
z_{LCB}	= Sinkage at LCB
$\mathrm{z}_{\mathrm{ND\text{-}LCB}}$	= Non-dimensional sinkage at LCB
z_{fwd}	= Sinkage at the forward post
z_{aft}	= Sinkage at the aft post
$\Delta x_{fwd\ post\ to\ LCB}$	= Longitudinal distance between the forward post and the LCB
$\Delta x_{between\ \mathrm{posts}}$	= Longitudinal distance between the posts
t	= Trim between perpendiculars
t_{ND}	= Non-dimensional trim betweeen perpendiculars
UKC_s	= Static under keel clearance

In this section, results obtained from the various aspects of the docking study are presented. Discussion arising from these results, and the implications on this transhipping concept, are provided in Section 3.4.

3.3.1 Effect of the well dock without vents

The effect that the well dock has on the feeder vessel performance is able to be determined by directly comparing the experimental results acquired in the open water condition against one (or more) of the cases where the feeder vessel enters or exits the well dock. For this purpose, the open water case with the feeder vessel moving astern is compared to the case where the feeder vessel enters the well dock (with no vents). The resultant comparison for the longitudinal force is shown in Figure 3.3 where the non-dimensional values are plotted as a function of (steady-state) vessel speed. Figure 3.4 shows the sinkage behaviour for the docking manoeuvre and Figure 3.5 shows the trim behaviour for this same comparison. Similarly, the longitudinal force comparison between the feeder vessel moving ahead in open water and the feeder vessel departing the well dock (with no vents) is presented in Figure 3.6. The sinkage behaviour is shown in Figure 3.7 and the trim is compared in Figure 3.8 for the feeder vessel moving ahead in open water and departing the well dock.

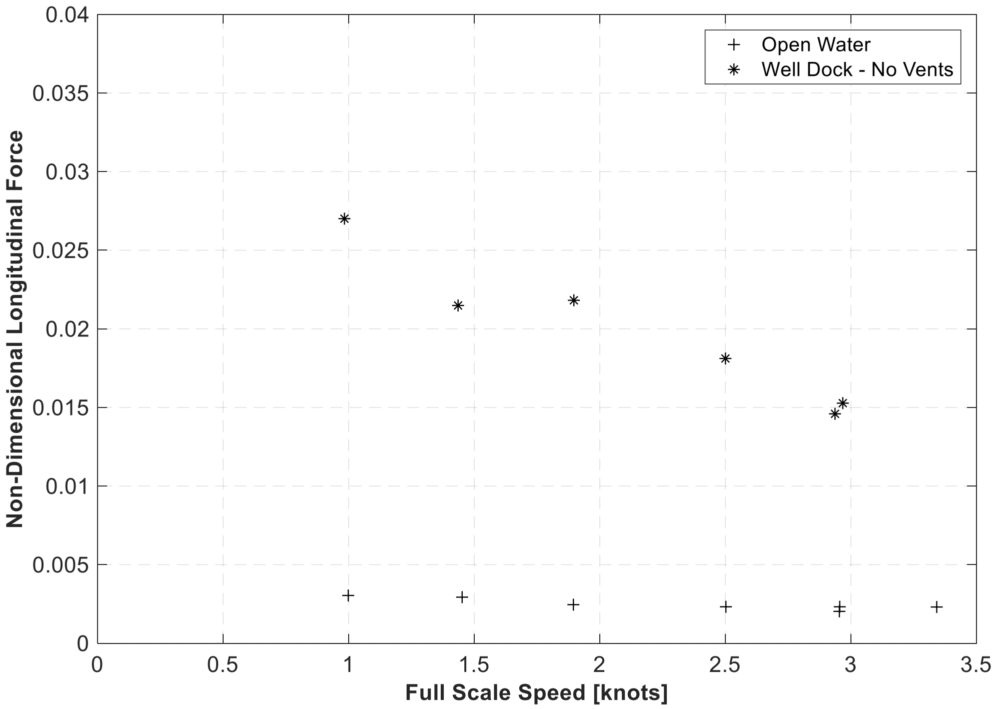

Figure 3.3: Non-dimensional longitudinal force as a function of vessel speed for the feeder vessel moving astern in the open water condition compared to the feeder vessel docking. Positive longitudinal force opposes the direction of motion.

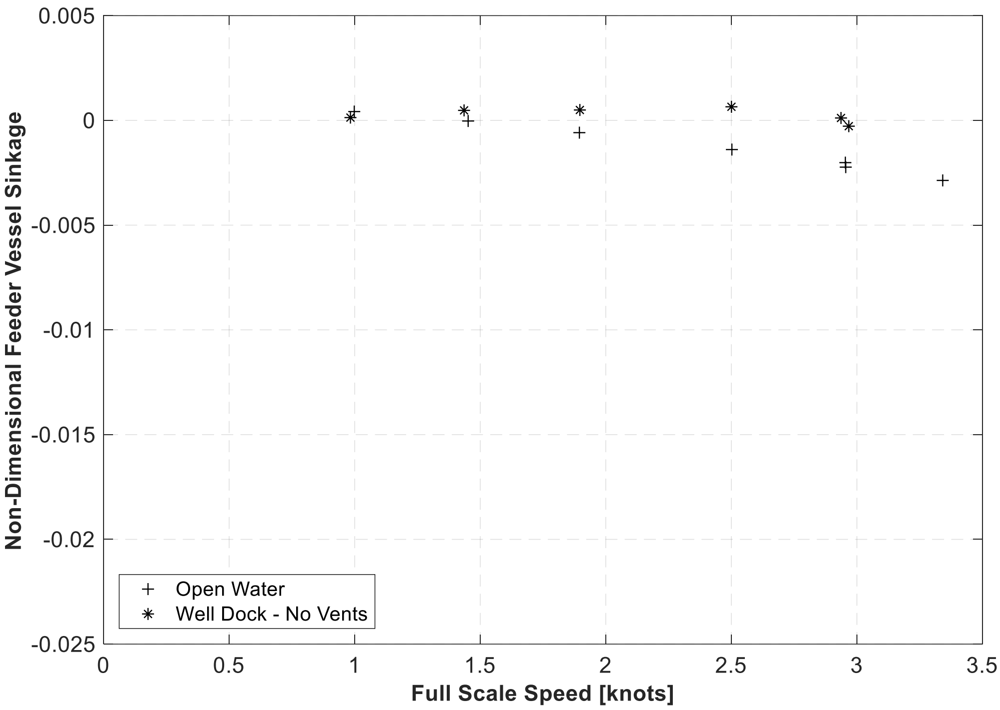

Figure 3.4: Non-dimensional sinkage as a function of vessel speed for the feeder vessel moving astern in the open water condition compared to the feeder vessel docking. Negative non-dimensional sinkage represents sinkage and positive values indicate rise.

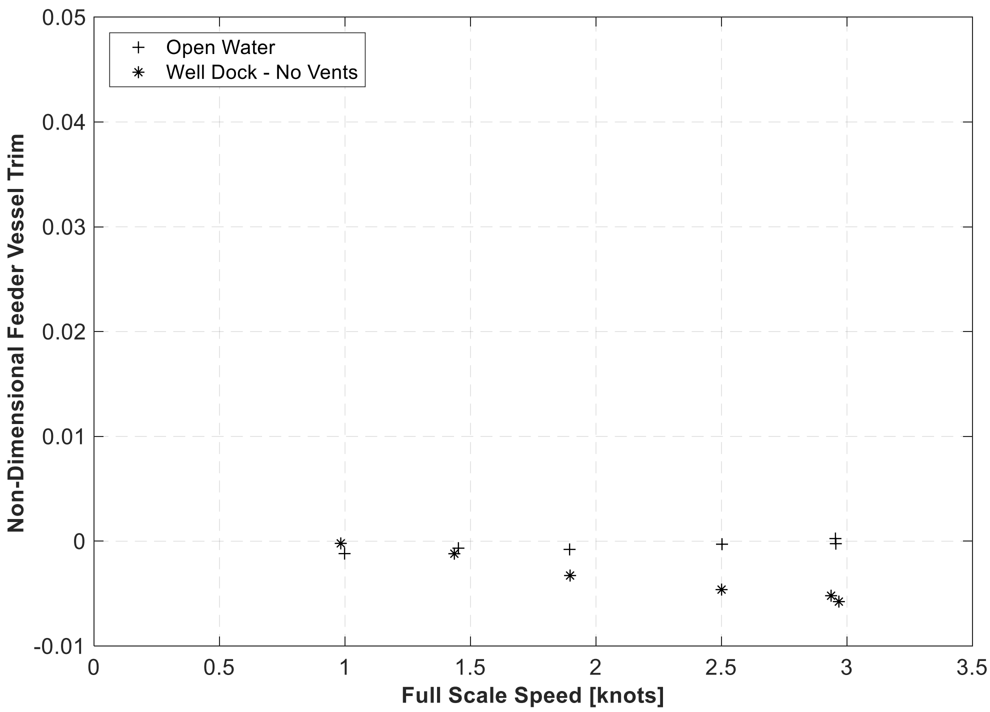

Figure 3.5: Non-dimensional trim as a function of vessel speed for the feeder vessel moving astern in the open water condition compared to the feeder vessel docking. Positive non-dimensional trim represents stern down rotation and negative values indicate bow down rotation.

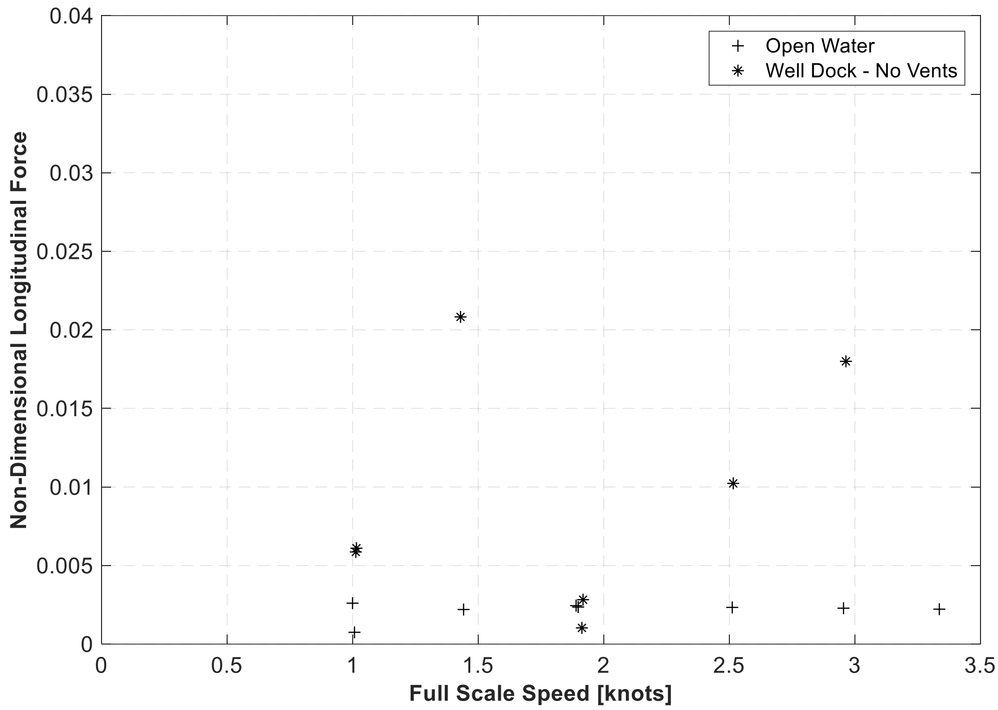

Figure 3.6: Non-dimensional longitudinal force as a function of vessel speed for the feeder vessel moving ahead in the open water condition compared to the feeder vessel departing the well dock. Positive longitudinal force opposes the direction of motion.

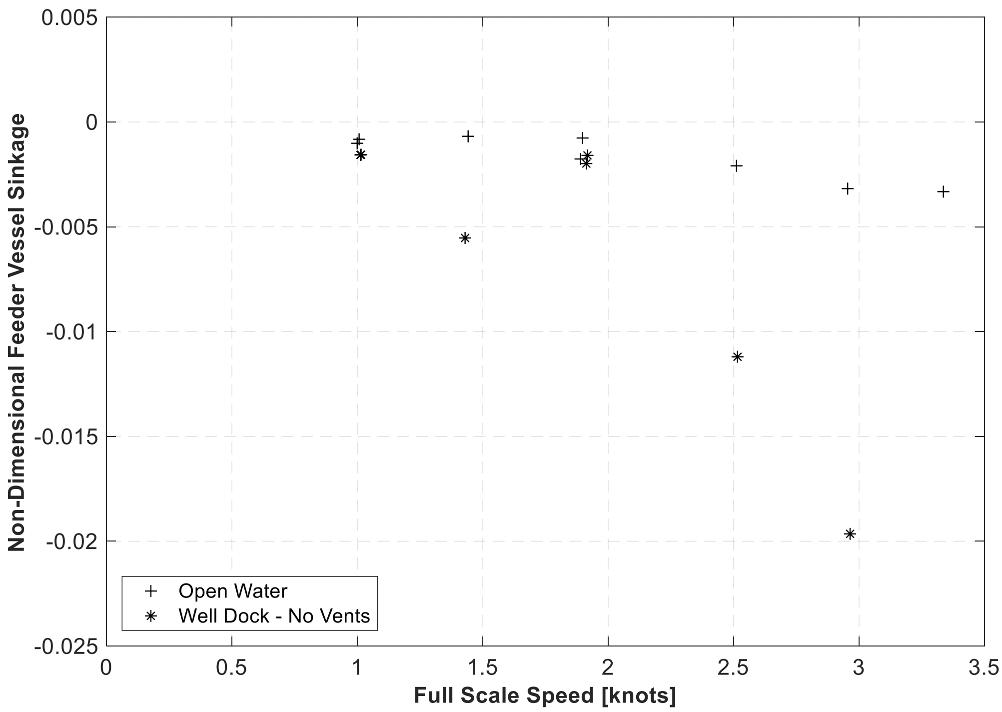

Figure 3.7: Non-dimensional sinkage as a function of vessel speed for the feeder vessel moving ahead in the open water condition compared to the feeder vessel departing the well dock. Negative non-dimensional sinkage represents sinkage and positive values are rise.

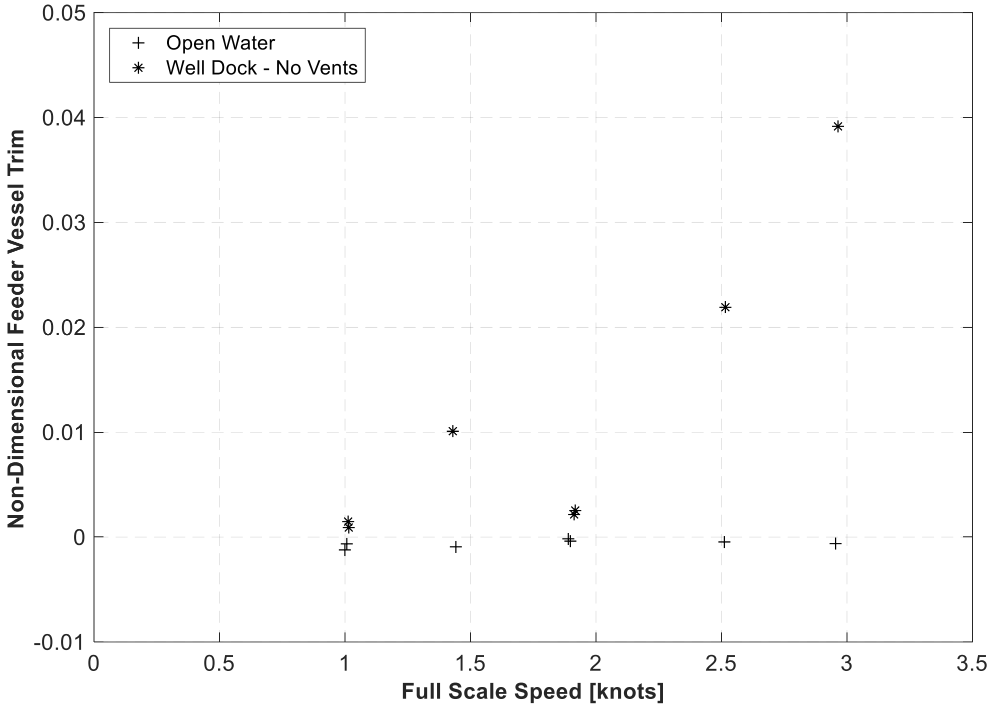

Figure 3.8: Non-dimensional trim as a function of vessel speed for the feeder vessel moving ahead in the open water condition compared to the feeder vessel departing the well dock. Positive non-dimensional trim represents stern down rotation and negative values indicate bow down rotation.

3.3.2 Effect of the well dock vents

Experiments were performed to investigate the effectiveness of the well dock vents to mitigate the effects of the confined water within the well dock as a feeder vessel enters or exits. In this section, the results from the three different open vent configurations and the no vent case are compared graphically to assess their effectiveness. For comparison, the results from the open water case are included in these comparisons.

The longitudinal force experienced by the feeder vessel has again been investigated as this parameter showed the clearest variation of those interrogated when comparing the well dock without vents and open water cases in Section 3.3.1. The longitudinal force on the feeder vessel while undertaking the docking manoeuvre for each of the four vent configurations and the open water scenario are presented as a function of vessel speed in Figure 3.9. These results are supported by the sinkage and trim for the feeder vessel docking within a well dock with varying vent openings as shown in Figure 3.10 and Figure 3.11 respectively.

The results for the feeder vessel departing the well dock and moving ahead through open water were also compared. The longitudinal force measurements are presented in Figure 3.12 for the three vent openings as well as the open water and well dock without vents conditions. Similarly, the sinkage behaviour is shown in Figure 3.13 and Figure 3.14 demonstrates the trim behaviour of the feeder vessel.

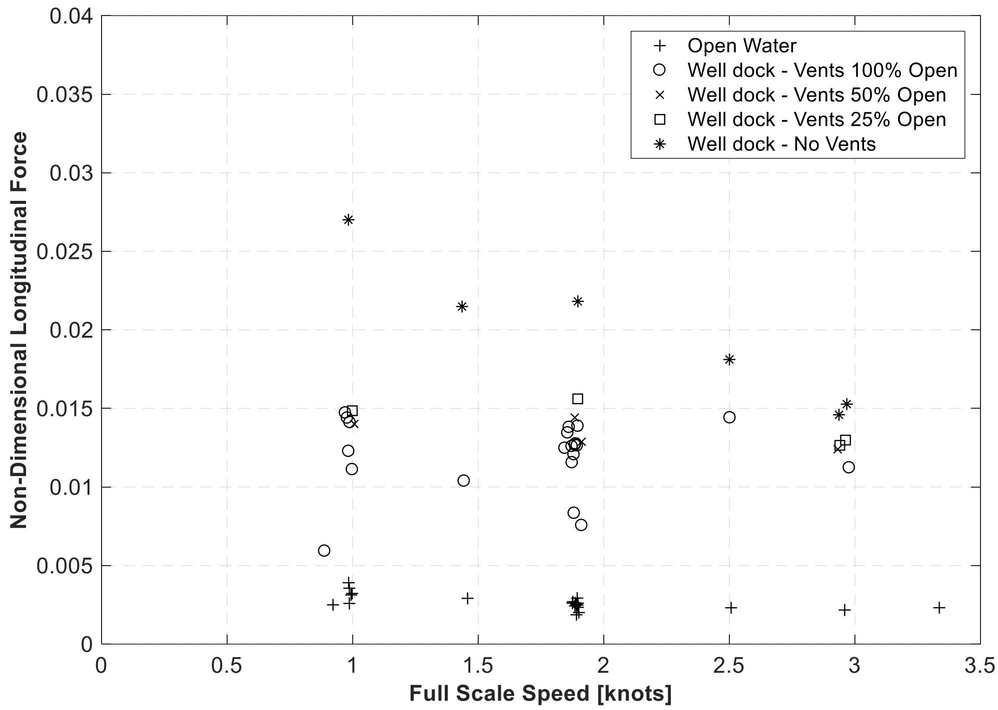

Figure 3.9: Non-dimensional longitudinal force on the feeder vessel moving astern in the open water condition and entering the well dock with no vents and the three well dock vent configurations. Positive longitudinal force opposes the direction of motion.

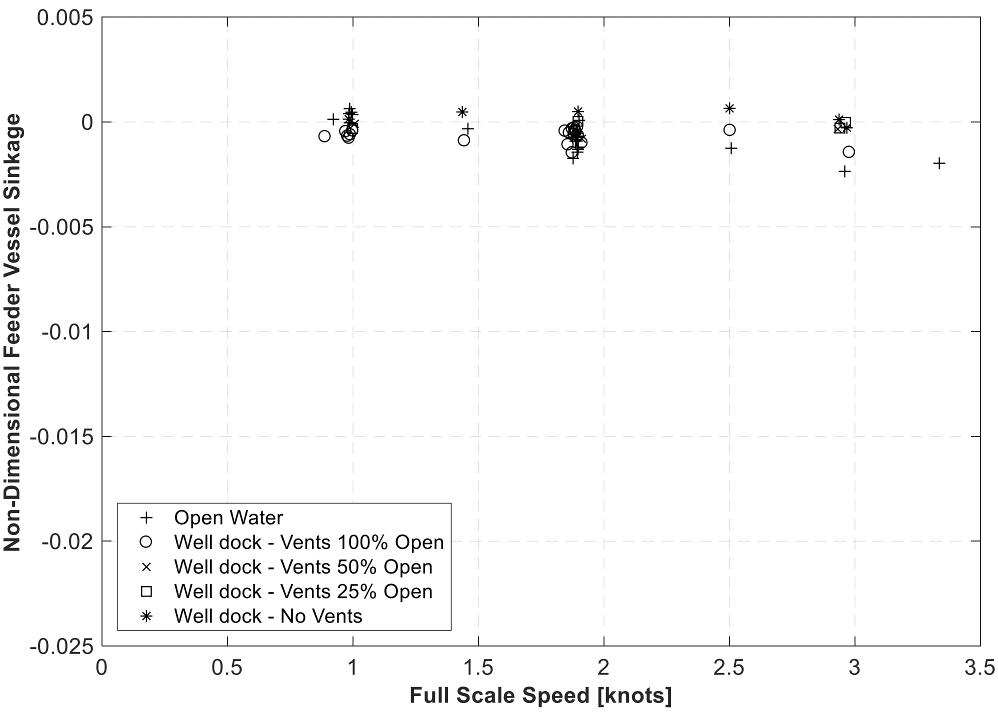

Figure 3.10: Non-dimensional sinkage of the feeder vessel moving astern in the open water condition and entering the well dock with no vents and the three well dock vent configurations. Negative non-dimensional sinkage represents sinkage and positive is rise.

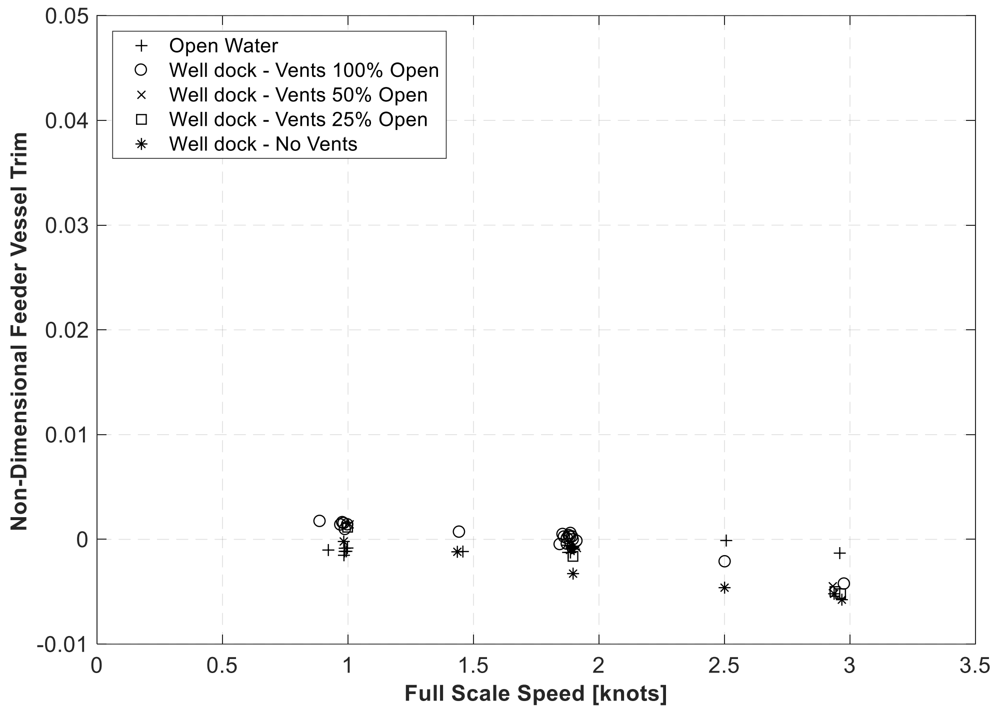

Figure 3.11: Non-dimensional trim of the feeder vessel moving astern in the open water condition and entering the well dock with no vents and the three well dock vent configurations. Positive non-dimensional trim represents stern down rotation and negative is bow down rotation.

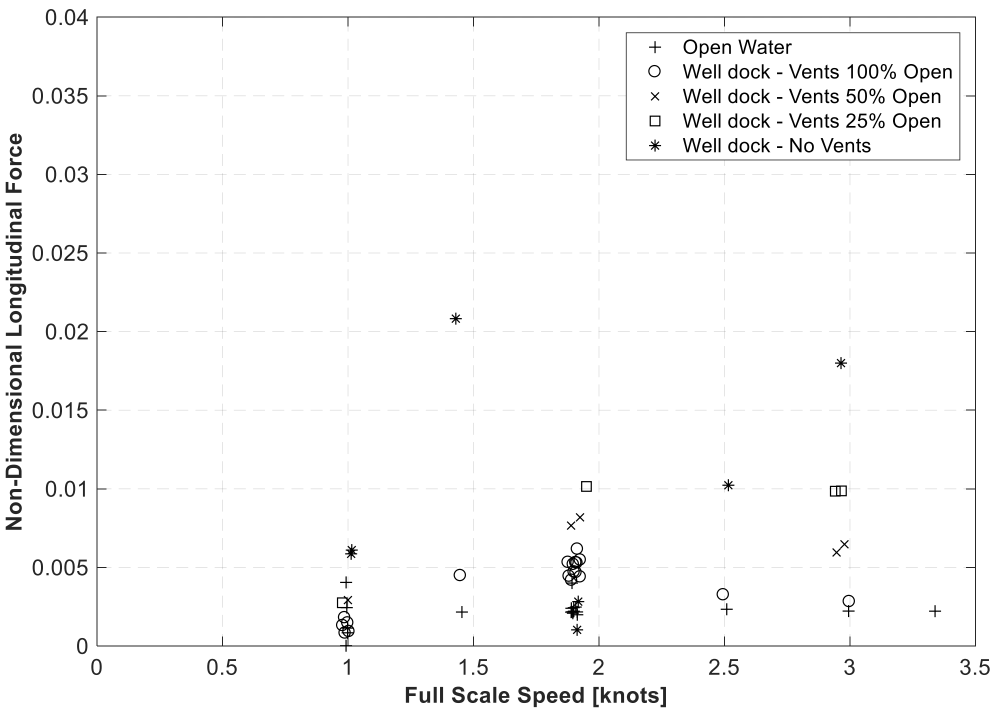

Figure 3.12: Non-dimensional longitudinal force of the feeder vessel moving ahead in the open water condition and departing the well dock with no vents and the three well dock vent configurations. Positive longitudinal force opposes the direction of motion.

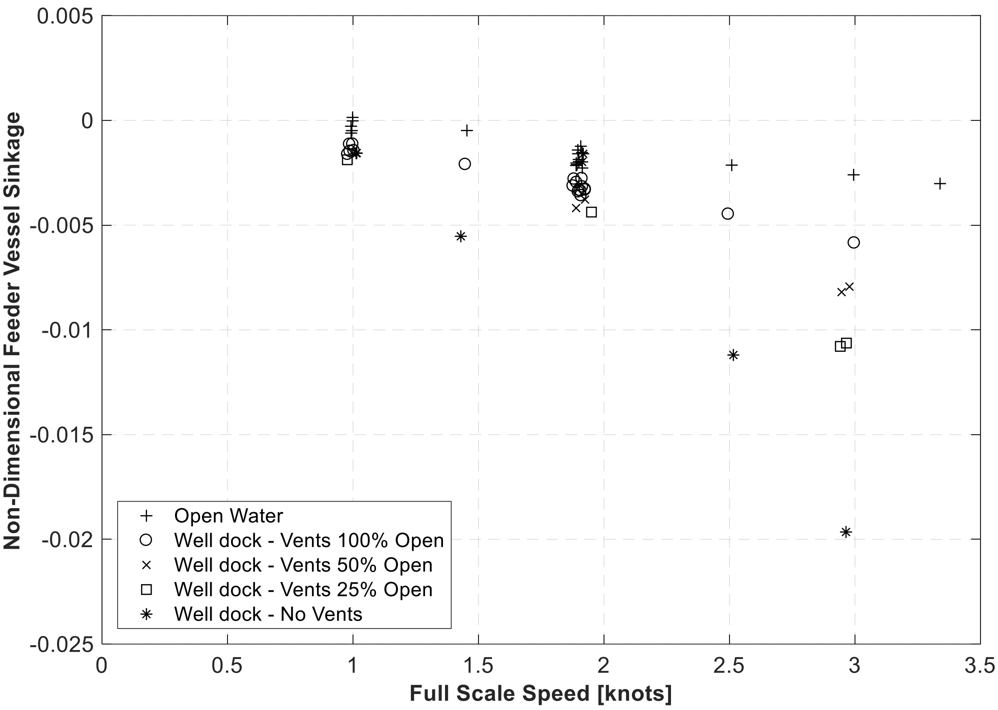

Figure 3.13: Non-dimensional sinkage of the feeder vessel moving ahead in the open water condition and departing the well dock with no vents and the three well dock vent configurations. Negative non-dimensional sinkage represents sinkage and positive is rise.

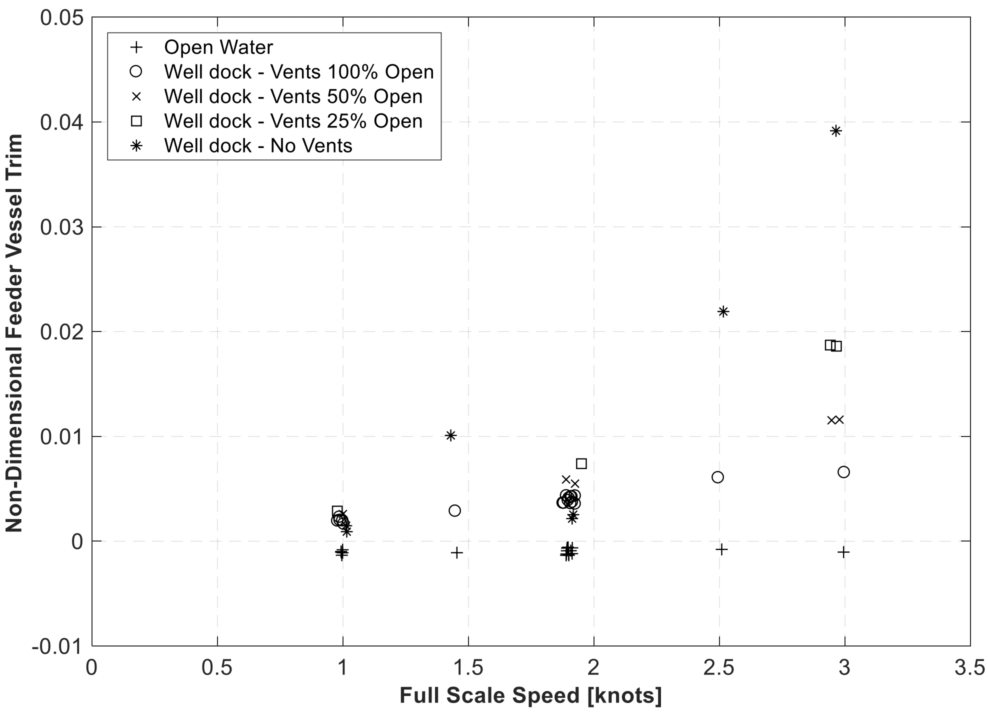

Figure 3.14: Non-dimensional trim of the feeder vessel moving ahead in the open water condition and departing the well dock with no vents and the three well dock vent configurations. Positive non-dimensional trim represents stern down rotation and negative is bow down rotation.

3.3.3 Combined effects of sinkage and trim

The sinkage and trim behaviour of the feeder vessel provides an indication of how the feeder vessel is behaving in the well dock and why it is behaving in such a manner. However, the sinkage and trim in isolation have very little practical application to the scenario where the feeder vessel docks within or departs from the well dock. The most important motion parameter when the feeder vessel is within the well dock is the clearance between the keel of the feeder vessel and the well dock floor. This under keel clearance combines the effect of the sinkage and trim under each of the conditions tested.

There is always one of two positions that are geometrically certain to demonstrate the minimum clearance between the vessels; the stern most edge of the well dock floor and the aft most point of the feeder vessel skeg. The clearance at each of these positions was calculated using the time series 6DOF motion data for each vessel. This analysis was performed for each run and the minimum of the two options was non-dimensionalised with respect to the static under keel clearance to give the change in minimum under keel clearance using the same method previously discussed. The resultant plot of change in minimum under keel clearance for the docking manoeuvre is shown in Figure 3.15 and the companion plot for the departure manoeuvre is shown in Figure 3.16.

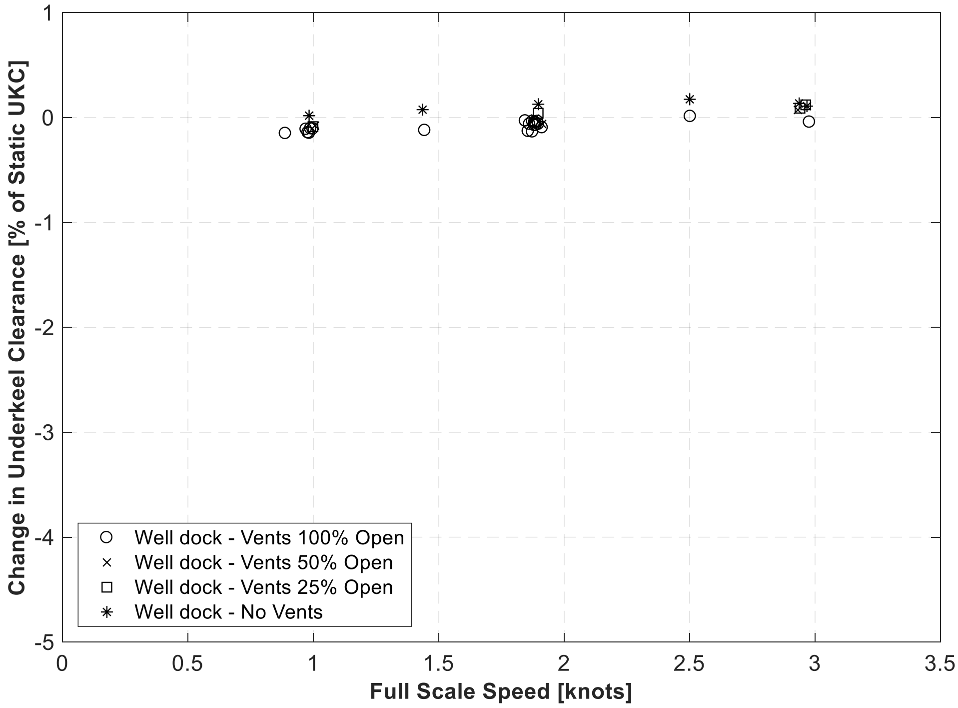

Figure 3.15: Change in under keel clearance due to the combined effects of sinkage and trim for the feeder vessel entering the well dock with no vents and the three well dock vent configurations. Negative change in static under keel clearance indicates a reduction in under keel clearance between the feeder vessel and the well dock floor. A -100% change would indicate contact between the vessels.

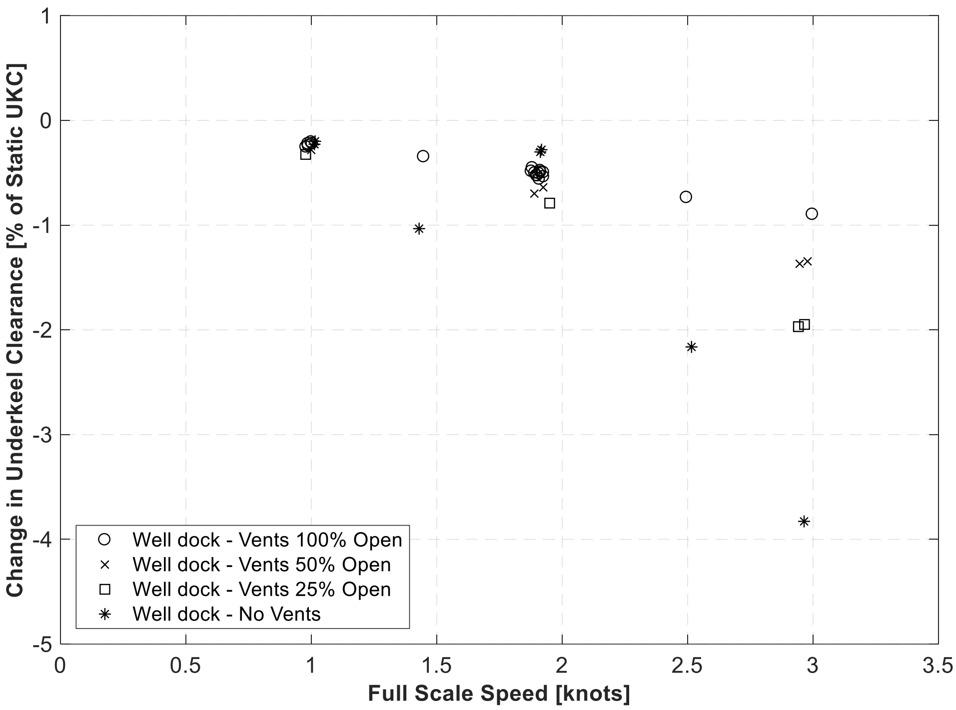

Figure 3.16: Change in under keel clearance due to the combined effects of sinkage and trim for the feeder vessel departing the well dock with no vents and the three well dock vent configurations. Negative change in static under keel clearance indicates a reduction in under keel clearance between the feeder vessel and the well dock floor. A -100% change would indicate contact between the vessels.

3.4 Discussion

3.4.1 Effect of the well dock without vents

The effect that the significant depth and width constrictions of the mothership well dock has on the feeder vessel performance was investigated by direct comparison against results for the same feeder vessel operating in fully deep, open water. In short, the effect of the well dock was found to be significant. It should be noted that all results presented in this section for feeder vessel performance while entering or departing the well dock refer to a well dock with no vents.

The feeder vessel demonstrates a relatively consistent non-dimensional longitudinal force with respect to speed when operating in deep, open water, either forward or astern, indicating a close speed-squared relationship, as might be expected. When the feeder vessel operates in the well dock the non-dimensional longitudinal force was found to be significantly higher than the open water case, particularly for the docking manoeuvre (Figure 3.3). It is noteworthy that the non-dimensional longitudinal force is trending downwards with increased vessel speed. This indicates that the dependence of force on vessel speed is at an index less than speed squared. Observation of the dimensional results showed that the longitudinal force did increase with increased speed but at a rate slower than speed squared. The longitudinal forces experienced during the departure manoeuvre (Figure 3.6) showed less distinct trends than the docking manoeuvre, however it was still generally found that the non-dimensional longitudinal force was significantly greater than the deep open water case.

The longitudinal force is perhaps the most crucial parameter for the implementation of a well dock for transhipment purposes as these trends indicate the effect that the well dock has on the force required to safely manoeuvre and propel the feeder vessel in/out of the well dock in a controlled manner. It is clear that in both the docking and departure cases that a significantly greater, and for the departure case much less predictable, force is required than the equivalent case in open water. This increase in force required to dock the feeder vessel is logical as the fluid that is being displaced must flow alongside and under the feeder vessel in order to escape the well dock, thus artificially raising the flow speed along the hull, resulting in an increase in frictional resistance. Furthermore, the increase in fluid flowing outward will cause a pressure gradient from high pressure at the forward end of the well dock to low pressure between the feeder vessel and the well dock before returning to hydrostatic pressure upon exiting the well dock. The increase in longitudinal force makes this parameter a good candidate to highlight the effectiveness of the various vent configurations in reducing the well dock effects on feeder vessel performance (refer Section 3.4.2).

For the feeder vessel sinkage, there is a clear trend demonstrating that there is more variation with speed in deep open water than within the well dock when the feeder vessel is docking (Figure 3.4). The open water dataset for the feeder vessel going astern shows that sinkage is sensitive to speed with the feeder vessel demonstrating a bodily sinkage that increases approximately linearly with increased speed. In contrast, when the feeder vessel enters the well dock (astern) its sinkage behaviour shows very little dependence on speed, with a relatively small bodily rise for most of the speeds investigated. The sinkage results for the feeder vessel travelling forward in open water (Figure 3.7) were slightly different than the equivalent astern case (Figure 3.4) with the dependence on speed only becoming apparent at speeds of 2.5 knots and above. However, there is inconsistency for the sinkage when the feeder departs the well dock in a similar manner to the longitudinal force data (Figure 3.6) with the two knot speed indicating very little variation between the well dock and open water scenarios for the departing feeder vessel.

The trim for both forward and astern deep, open water scenarios was found to be very small across all tested speeds. It is clear that the well dock constriction affects the trim of the feeder vessel for both the docking and departing manoeuvres, as there are significant differences from the open water behaviour. For the docking case, there is a clear dependency on feeder vessel speed, with trim transitioning from even keel at low speeds to bow down at higher speeds (Figure 3.5). In this case the correlation with feeder vessel speed is quite linear. There are less clear trends for the departing case (Figure 3.8) but there is a general trend for increased speed to cause significantly increased stern down trim. Again it is noted departing the well dock has less effect on the trim at one and two knots.

The feeder vessel was found to rise and trim down by the bow when docking and to sink and trim down by the stern when departing. This is likely due to the high pressure region that was hypothesised to be contributing to the increased longitudinal force. This is in contrast to the expected confined water effects which most often cause a bodily sinkage and a trim dependant on the location of the longitudinal centre of buoyancy (LCB) (Millward, 1990). In this case due to only the aft end of the feeder vessel being subject to the confined water, a stern down trim would be expected. When the feeder vessel is departing the expected behaviour is observed with a bodily sinkage and a stern down trim. It is expected that as the feeder vessel departs and the water is trying to flow back into the well dock past the feeder vessel the increased fluid flow velocity yields a low pressure region that extends through the entire well dock as there is no open passage to enable pressure recovery at the forward end of the well dock. This low pressure region is expected to yield a reduced free surface height and the stern of the feeder vessel therefore falls, accentuating the stern down trim and sinkage.

Most previous research on vessels in restricted and confined water focus on a waterway that is not blocked at one end, as is the case with the well dock. In such cases all the fluid is not required to flow past the moving vessel opposite to the direction of travel. This yields a more traditional pressure field whereby there are high pressure regions ahead and stern of the vessel with a low pressure region along the midbody of the vessel. It is hypothesised that the effect of the well dock being an enclosed volume with only one opening is causing the somewhat counter intuitive rise at the stern of the vessel as it is docking and an accentuated confined water effect as the vessel departs.

3.4.2 Effect of the well dock with vents

A comparison between the open water scenario, the well dock with three different vent configurations and the well dock with no vents was used to investigate if the effectiveness of well dock vents for mitigating the confined water effects generated by the well dock. The longitudinal force of the feeder vessel was expected to be the most telling parameter for demonstrating the vent effectiveness for both the docking and departure manoeuvres.

When the feeder vessel is docking, the non-dimensional longitudinal force results (Figure 3.9) show that the three vent configurations fall between the open water scenario and the no vents condition. The three vent opening configurations are well distributed between the open water and well dock with no vent configurations at low speed but begin to cluster towards the no vents configuration at three knots. This indicates that the vents are effective when the feeder vessel is docking at speeds of up to two knots.

The same comparison was performed for the departure manoeuvre and clearer trends were observed (Figure 3.12). When the feeder vessel is departing the well dock the non-dimensional longitudinal force generally increases as the vent size is reduced. There is an exception to this trend at two knots where the longitudinal force for the well dock with no vents configuration was similar to the open water scenario. These trends indicate that the well dock vents are effective across the speed range tested. It is noteworthy that generally the 100% open vent configuration yielded a force behaviour most like the open water scenario and the 25% open vent configuration yielded behaviour most like the well dock with no vents configuration. This supports the hypothesis that the vents within the well dock reduce the confined water effect and larger vent openings are more effective.

The trim and sinkage behaviour of the feeder vessel were not expected to demonstrate the effectiveness of the well dock vents very clearly due to the less significant differences observed in the initial well dock comparison, particularly when the feeder vessel enters the well dock (Figures 3.4 and 3.5). Once again a comparison was made between the three vent configurations, the open water scenario and the well dock with no vents for the sinkage behaviour while docking (Figure 3.10), where the results didn’t show any clear trends with all conditions yielding small sinkage values. When the feeder vessel was departing (Figure 3.13), there was found to be more variation between conditions but the only clear trend appeared at the three knot feeder vessel departure speed. Here, an increased vent opening was found to reduce the sinkage of the feeder vessel when departing the well dock.

The trim behaviour was compared in a similar manner and the results were seen to be very similar to the sinkage results. The trim behaviour while the feeder vessel was docking (Figure 3.11) was found to be very similar to the equivalent sinkage behaviour with all conditions clustering at small trim values. The trim while departing the well dock (Figure 3.14) was also similar to the sinkage behaviour when the feeder vessel was departing the well dock demonstrating more variation than the docking manoeuvre with the clearest trend being observed at three knots. Here it was again clear that a larger well dock vent is more effective at mitigating the confined water effects of the well dock. A similar trend to that which was observed with the longitudinal force results is again present in the trim behaviour when the feeder vessel is departing the well dock at two knots.

When viewing the entire dataset as a whole it is clear that there is consistent evidence that the feeder vessel is acting somewhat like the piston of a plunger in a syringe. This causes a high pressure region (observed to be manifested as a higher free surface elevation) to form in the forward end of the well dock when the feeder vessel is docking. The fluid moves from high to low pressure past the feeder vessel, thus causing a low pressure region along the length of the feeder vessel before returning to hydrostatic pressure outside the well dock. The traditional vessel sinkage and trim expected due to the low pressure around the feeder vessel is offset by the increased free surface elevation at the forward end of the well dock. All of these effects are reduced to some extent by the introduction of the various well dock vents. The fluid is now able to escape through the side of the well dock at the innermost end so there is lower fluid flow past the feeder vessel and less pressure build up at the forward end of the well dock.

When the entire dataset for the feeder vessel departing the well dock is considered very similar trends can be observed. When there are no well dock vents, the feeder vessel departing causes a significant local low pressure (and corresponding lowered free surface elevation) at the forward end of the well dock. This low pressure is attempted to be filled by fluid flowing past the feeder vessel at a higher velocity thus causing low pressure along the vessel length. In this situation the two effects are working together rather than in opposition which causes a lower pressure beneath the feeder vessel. The introduction of the well dock vents allows fluid to be drawn in behind the feeder vessel thus reducing both of these effects simultaneously. Once again a larger vent opening is found to cause a larger reduction in confined water effect.

The well dock vents were found to reduce in effectiveness in the docking manoeuvre as the feeder vessel speed was increased beyond two knots where the datasets began to show measured parameters for the well dock vent configurations clustering more closely with the well dock without vents scenario. This is likely due to the energy being pushed ahead of the feeder vessel no longer being able to escape quickly enough through the vent opening. This reduction in effectiveness was not observed within the departing conditions because any energy being forced ahead of the feeder vessel upon departure is propagating towards open water.

3.4.3 Combined effects of sinkage and trim

The change in under keel clearance during the docking manoeuvre was found to be very close to zero across the entire speed range for all four vent configurations as can be seen in Figure 3.15. This is also consistent with the sinkage and trim behaviours observed and highlights that any confined water effect that may have been present in an infinite length channel is counteracted by the well dock end effect.

The change in under keel clearance during the departure manoeuvre was found to be much more dependent on speed and vent configuration. Increased speed caused increased reduction in under keel clearance with the exception of the two knot speed. The introduction of the well dock vents was also demonstrated to be effective during the departure manoeuvre with the 100% open vent condition showing significantly less reduction in under keel clearance than the no vents condition. There was no clear effect of the well dock vents at one or two knots.

Although of interest, the trim and sinkage are less significant from an operational point of view for the vessel load conditions under investigation as there were no instances where the under keel clearance became too low, such that impact between the feeder vessel and the well dock floor may occur. Across the entire scope of investigation, the maximum reduction in under keel clearance due to the combined effects of sinkage and trim was less than 6% of the static value. If the sinkage or trim motion were to be significant with respect to the under keel clearance between the vessels then these parameters could indicate potential contact occurring between the vessels during docking or departure manoeuvres. This was not the case for this scope of investigation however this could be different should the effect of propulsors be included or the static under keel clearance is reduced as may occur when different hull forms or loading conditions are encountered. The sinkage and trim behaviour would also become of more importance when considering the combined effects of vessel motion due to an external wave environment that would vary the under keel clearance over time.

3.4.4 Correlation to existing literature

Vessels operating in restricted water of infinite length have been previously discussed in the work of Tuck and Taylor (1970) who applied a one-dimensional approximation to explain the trim and sinkage behaviour of a vessel transiting a confined water environment (finite depth and width). When the combination of blockage and vessel speed reach a critical value the flow regime changes from sub- to trans-critical. In the latter regime energy is propagated ahead of the vessel. Tuck and Taylor (Tuck and Taylor, 1970) defined the boundary between sub- and trans-critical flow for an infinitely long waterway using a one-dimensional approach, as can be seen in Figure 3.17. The cases in the present study are shown on the figure and some lie within the trans-critical flow regime, based on a waterway of infinite length. In our case the end wall of the well dock adds another restriction to the flow. Hence, the energy propagated ahead of the feeder vessel can become 'trapped' between the end of the feeder vessel and the end of the well dock.

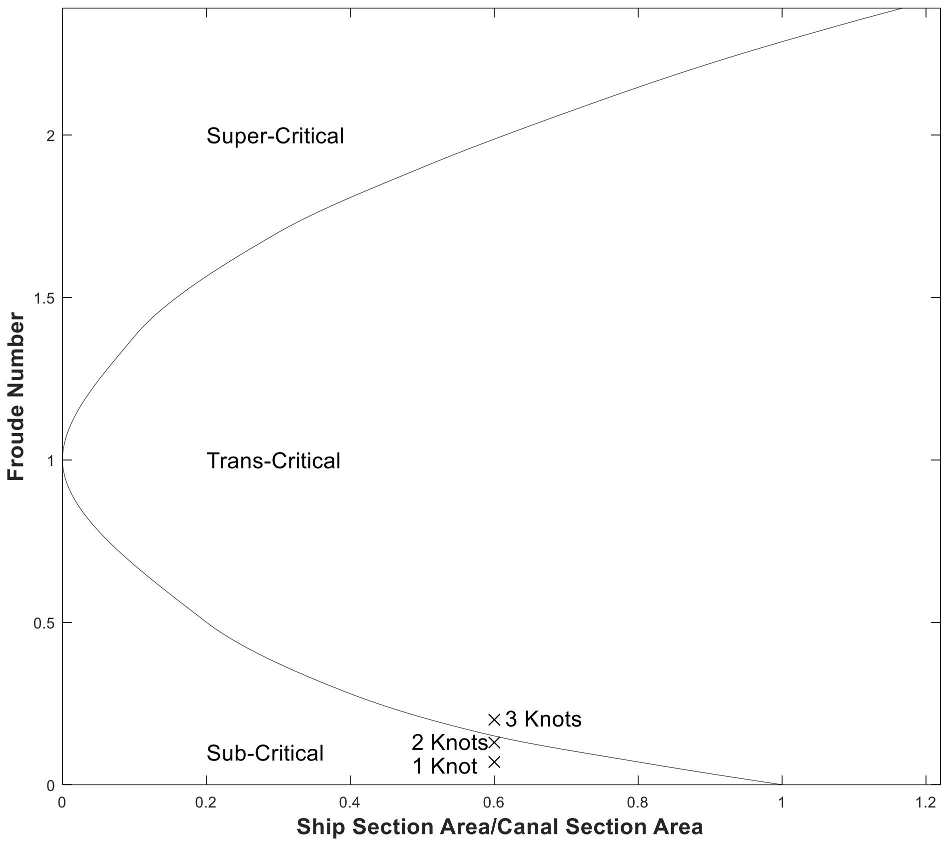

Figure 3.17: Froude depth number plotted against the blockage ratio showing the sub-, trans- and super critical regions of flow as defined by Tuck and Taylor (1970). The three main experimental speeds of the current investigation have been super imposed on this plot as can be seen at a blockage ratio of 0.6.

This is consistent with some of the visual observations during the experiments and trends in the results. This could explain the phenomena observed at the two knot feeder vessel speed as this is seen to fall very close to the boundary between sub- and trans-critical flows in Figure 3.17. The trapped energy is also consistent with the counter intuitive sinkage and trim results seen when the feeder vessel is docking (particularly with smaller vent sizes).

3.5 Broader implications

This investigation of a generic mothership indicates that the docking performance of the feeder vessel into the FHT will benefit from the inclusion of well dock vents. The similarities between the generic well dock tested and the FHT well dock indicate that the maximum size vents tested are far larger than is required. It is hypothesised that venting requirements for the generic well dock may be larger than those of the FHT because the geometry will encourage smoother flow with less separation. These factors combine to indicate that the ideal well dock vent size for the FHT is close to one quarter of the size of the maximum investigated (i.e. the 25% open configuration) under the conditions tested. The tested conditions consider the seakeeping performance of the vessels in a seaway while docked as well as the docking and departure manoeuvres in calm water. They do not account for the presence of a seaway while the feeder vessel is docking or departing the well dock.

The feeder vessel is proposed to dock (and depart) so slowly that the effect of feeder vessel speed on the wave encounter frequency will be quite small. Considering this, one approach to account for the presence of a seaway could be to superimpose the motion of the feeder vessel in open water with the response observed during the calm water docking. If both components are small relative to the static under keel clearance then this approach may yield reasonable results. This approach also relies on the assumption that the sea state within the well dock and the region aft of the well dock are not significantly affected by the FHT. From the results presented in Chapter 2, it is now known that this is not the case for the sheltered region aft of the FHT where the wave height can be significantly reduced in the lee of the FHT but the sea state inside the well dock is still unknown. Previous studies on the sea state and the motion of landing craft inside amphibious vessels have found that there is an artificial sea state generated within the well dock (Bass, et al., 2004, Cartwright, et al., 2006, Cartwright, et al., 2007) but to the author's knowledge a similar investigation for vented well docks has never been undertaken.

A preliminary study was conducted in an attempt to quantify the environment within the well dock for each of the various vent options. The work of Tsoukala, et al. (2014) (as discussed in Chapter 1) indicated that larger vents would likely lead more energy within the well dock. Experimental tests were performed using the scale model of the mothership with various well dock vent sizes which was free to pitch, heave and roll. For this preliminary study the environment inside the well dock monitored using wave probes attached to mothership model at two locations, the forward and aft ends. These measurements were interrogated to support visual observations that identified wave periods and vent configurations that demonstrated hazardous conditions within the well dock.

Incident wave periods longer than 14 s lead an environment more severe than incident waves while shorter wave periods lead to a sheltering effect within the well dock. The vent size also influenced the well dock environment with the largest vents resulting in the least variation from the incident sea state over wider range of wave periods. These same trends were observed at both the forward (closed) and aft (near the entrance) ends of the well dock. Overall this preliminary investigation indicates that both the wave period and the vent configuration have a large effect on the environment within the well dock.

The feeder vessel seakeeping has previously been shown to be more favourable across all incident wave periods when docked (as compared to in open water) while at some wave periods, the environment within the well dock is less favourable than the open water conditions. This is likely caused by the presence feeder vessel having a significant effect on the environment within the well dock. These factors indicate that it is not yet possible to predict the effect of an incident sea state on the docking and departure manoeuvres of the feeder vessel.

These preliminary findings give an insight into the environment within the well dock while there is no feeder vessel present. They indicate that there may be a narrow range of incident sea states that prevent the feeder vessel from entering where it would be otherwise safe to depart or remain within the well dock if it were already docked. Under these conditions where long incident wave period is causing large variations in well dock depth, the relative motion between the vessels when subjected to the same incident sea states was discussed in Chapter 2. Comparison with Figure 2.14 clearly shows that the deteriorating well dock environment aligns with significant reduction in minimum under keel clearance. However the smaller vent sizes (vents 25% and 50% open) were least favourable in terms of well dock environment but were more favourable in terms of reduction in minimum under keel clearance.

From observations while conducting the experiments the adverse well dock environment could be due to a large phase difference between the incident sea state (and hence FHT pitch motion) and the sloshing effect within the well dock. This phase difference combined with the reflections from the bluff end wall of the well dock lead to generate large waves and under some circumstances standing waves within the well dock. It should also be noted that there may be the possibility of environments within the well dock that cause damage to the materials handling equipment or water ingress to the cargo deck. These are unfavourable conditions that may lead to downtime completely independent of accelerations and velocities due to the motion response of the FHT.

Potential mitigation for these effects could be the inclusion of wave damping geometrical features such as a sloped forward end of the well dock or gates on the open end of the well dock. Further investigation could better quantify the well dock wave environment and reveal the severity of these effects on the operational envelope of the FHT concept, determining if mitigation is required.

3.6 Concluding remarks

An experimental campaign has been undertaken to investigate the operational complexities that occur when a feeder vessel moves into a well dock whose cross section is only slightly larger than itself. The parameters of interest for this study were the longitudinal force on the feeder vessel and the sinkage and trim behaviours. Both the docking (feeder vessel moving astern into the well dock) and departing (feeder vessel moving ahead as it exits the well dock) manoeuvres were investigated across a range of speeds from one to three knots full scale. The longitudinal force highlighted the effect of speed and the sinkage and trim highlighted any potential grounding issues. The effect of the well dock itself was identified by comparison with a deep, open water scenario and the effectiveness of well dock vents for mitigating these effects was determined by comparing three different vent configurations.

It was shown that there is a significant effect on feeder vessel performance when introducing the well dock compared to open water. There was a marked increase in the longitudinal force of the feeder vessel when undertaking both the docking and departure manoeuvres. This was identified to be the most important factor for the real world application because this increase in force indicates that more, and much less predictable, thrust will be required and the response time of the feeder vessel will be increased which is detrimental in confined manoeuvring situations such as this.

The introduction of the well dock was found to negate the small bodily sinkage that was observed in open water and to cause small bow down trim while docking the feeder vessel. These effects while docking the feeder vessel were found to be counter intuitive to what would be expected for a vessel operating in an infinitely long confined water scenario. This experiment did not correlate with findings on confined water scenarios of infinite length that have been previously published. This was attributed to the effect of the forward end of the well dock. The feeder vessel sinkage and trim behaviour while the feeder vessel was departing was found to be as expected with a bodily sinkage and stern down trim, however it was found that the forward end of the well dock accentuate these effects.

A clear benefit to including well dock vents was observed for both the docking and departure manoeuvres. This was most clearly observed in the non-dimensional force as well as the trim and sinkage behaviour when the feeder vessel is departing at speeds above two knots. It was noted that the vent effectiveness was reduced when the feeder vessel was docking at a speed of three knots. Thus, it can be concluded that the inclusion of the well dock vents does produce a measurable mitigation to the confined water effects due to the well dock. It was also noted that a larger vent is more effective than a smaller vent.

The confined water effect for sub-critical flow typically increases the fluid velocity past the feeder vessel, which leads to a low pressure region adjacent to the vessel causing a bodily sinkage and trim. When the feeder vessel was docking inside the well dock without vents it was found to be counter acted by a high pressure region at the forward end of the well dock, which caused counter intuitive sinkage and trim behaviour to be observed. This effect was mitigated by the introduction of well dock vents when the feeder vessel was docking at speeds lower than three knots, however at this speed this was not the case. This reduction in vent effectiveness was partly attributed to the flow transitioning into the trans-critical regime causing energy propagation ahead of the feeder vessel.

When the feeder vessel was departing the well dock without vents it was concluded that the fluid was not able to flow inwards fast enough past the exiting feeder vessel to equalise a low pressure region in the forward end of the well dock. This combined with the traditional confined water effects to cause an accentuated bodily sinkage and stern down trim. The introduction of well dock vents allowed fluid to flow from the forward end of the well dock, notably reducing the above effects.

Preliminary investigation into the environment inside the well dock revealed that it is not feasible to superimpose the feeder vessel seakeeping performance over the calm water docking motion due to the well dock environment. These results also indicated a potential for the environment within the well dock to become hazardous to materials handling equipment or to cause green water ingress to the cargo hold. It was also noted that there may be certain sea state and vent combinations where the feeder vessel is able to remain in or depart from the well dock but would not be able to begin docking. It was also shown that a large well dock vent reduced the severity of the environment within the well dock, contradicting the seakeeping performance findings of Chapter 2.

CHAPTER 4

Insights into the flow within the well dock of a mothership during feeder vessel docking manoeuvres

4.1 Introduction

The unique hydrodynamics that occur within the scenario posed when the feeder vessel enters or exits the mothership well dock, including the effect of these vents, is a focal point of this chapter. Given the distinctively novel application, much of the research performed and reported here has required an approach predominantly based on physical scale model experimentation. Early attempts to simulate the complex fluid flow using a numerical approach highlighted the essential need to validate against relevant experimental data, of which nothing suitable or directly relevant was found in the public domain.

There were several interesting phenomena observed while investigating the docking manoeuvre in Chapter 3. The inclusion of vents yielded less longitudinal force on the feeder vessel but had little effect on the trim and sinkage behaviour. It was identified that the finite length of the well dock had a significant effect on the feeder vessel that was most visible during the docking operation where it caused a bow down trim and a bodily rise. This behaviour was found to be contrary to the traditional confined water motion response and was hypothesised to be caused by the propagation of energy ahead of the feeder vessel that is not able to escape the well dock, potentially due to the fluid flow transitioning into the trans-critical regime as defined by Tuck and Taylor (1970).

Reasons were hypothesised for the confined water behaviour exhibited by the feeder vessel when docking or departing the well dock, however the type of data acquired, namely vertical motions and longitudinal forces, was inadequate to conclusively prove these hypotheses to be true. This latest stage of the project, reported in this chapter, is focussed on utilising flow visualisation techniques to further support these findings. The method adopted was particle imaging velocimetry (PIV) using a LaVison sCMOS 5-megapixel camera for image capture and a pulsed laser sheet to illuminate fluorescent particles in the plane of interest. Two images are captured with a very short and precisely controlled interframe time which allows the path of the particles to be tracked through time. PIV has a wide variety of applications and there is ongoing active research developing this measurement technique for new applications to enable increased measurement precision of increasingly complicated flow fields. For example, PIV has been adopted to capture detailed maritime hydrodynamic flow field properties in and around structures and objects including ocean wave energy converter devices (Fleming and Macfarlane, 2017) and vessel control and lifting foils (Ashworth Briggs, et al., 2014).

This experiment applies a widely validated 2D PIV technique to this novel application to capture the complex flow within the well dock and to visualise the variations that occur between the selected vent configurations. The scope of these initial experiments cover a practical range of vessel speeds and flow restrictions, which lead to a wide range of expected flow conditions. The primary objective from this study is to compare the flow within the well dock between four vent configurations when the feeder vessel enters and exits the well dock of the mothership. A detailed study is warranted to confirm the need for vents and their size due to the significant impact on the structural design of the mothership and controllability of the feeder vessel.

Flow visualisation techniques are often employed to allow researchers to observe the fluid flow within a domain of interest and can be used to better explain a measurement or trend that is contrary to what is expected. Flow visualisation experiments or simulations are also often performed when the researcher has limited knowledge on what to expect from a given scenario. With the increased accessibility and measurement abilities of non-contact flow visualisation techniques during modern times, such techniques are now adopted as a primary data source. For example, Jurgens, et al. (2006) applied PIV techniques to visualise the flow around a scale model of a 300m LNG carrier operating in confined water in the MARIN shallow water test basin. The data obtained contributed to a better understanding of shallow water effects on the prediction of the hydrodynamic derivatives, and accelerated the development and validation of numerical prediction methods such as potential flow, RANS and semi-empirical simulation codes. The authors concluded that the flow characteristics were very promising for future CFD validation and that the PIV measurement system was found to be very robust and reliable, even in very shallow water conditions. There are several procedural handbooks and benchmark investigations available to assist facilities to introduce PIV measurement capabilities into their repertoire. Three such examples include a very application-focussed guide by Raffel, et al. (2013); the PIV benchmark tests as published by Muthanna, et al. (2010) and the International Towing Tank Conference (ITTC) guidelines for both 2D and 3D PIV benchmark tests and data repository (Fu, et al., 2017).

4.2 Experiments

An experimental program was undertaken using 2D PIV to measure and visualise the fluid flow within the well dock during feeder vessel manoeuvres. The flow was captured for both the inbound (feeder vessel docking) and outbound (feeder vessel departing) manoeuvres to investigate the effect that various well dock ventilation conditions has on the flow field.

The experimental program was undertaken at the Australian Maritime College (AMC) utilising the 35 m long by 12 m wide finite depth wave basin using a process very similar to the docking/departure experiments. Slight modifications were made to the experimental apparatus to enable flow visualisation techniques to be incorporated. Calm water docking tests were conducted whereby the feeder vessel model was towed using a carriage mounted on two parallel rails which enabled the model to be towed in a controlled manner with precise and consistent location, acceleration and velocity profiles. The feeder vessel started a docking (inbound) run and ended a departure (outbound) run at a position approximately four feeder vessel lengths away from the docked position. The docked position was set to be 35 mm (2100 mm full scale) between the transom of the feeder vessel and the end wall of the well dock (see Figure 4.1). The acceleration and deceleration rate of the feeder vessel was consistent and linear for all runs. This consistency in both the docked position and the ramp rates allowed the flow within the well dock to be interrogated at a very reliable and consistent position that was the same for each speed in both directions. This ensured that any variation observed between speeds or vent configuration was a product of the independent variable rather than analysing a slightly different portion of the position domain data.

For these experiments the mothership model was substituted for a purpose-built apparatus that accurately represented the well dock and vents (when appropriate) while providing dry regions for the camera, laser sheet optics and mirrors required for capturing the PIV images. The experimental apparatus was designed such that there was easy access to align the mirrors inside the sunken pit using the live stream from the camera. The PIV frame was then calibrated in-situ to minimise potential systematic error. The internal shape of the well dock remained identical to the mothership model but only the internal faces of the well dock and vents were modelled as shown in Figure 4.1. The well dock and vent model was constructed primarily using Perspex to allow visibility through the floor of the well dock for the camera and the transmission of the laser sheet through the walls of the well dock.

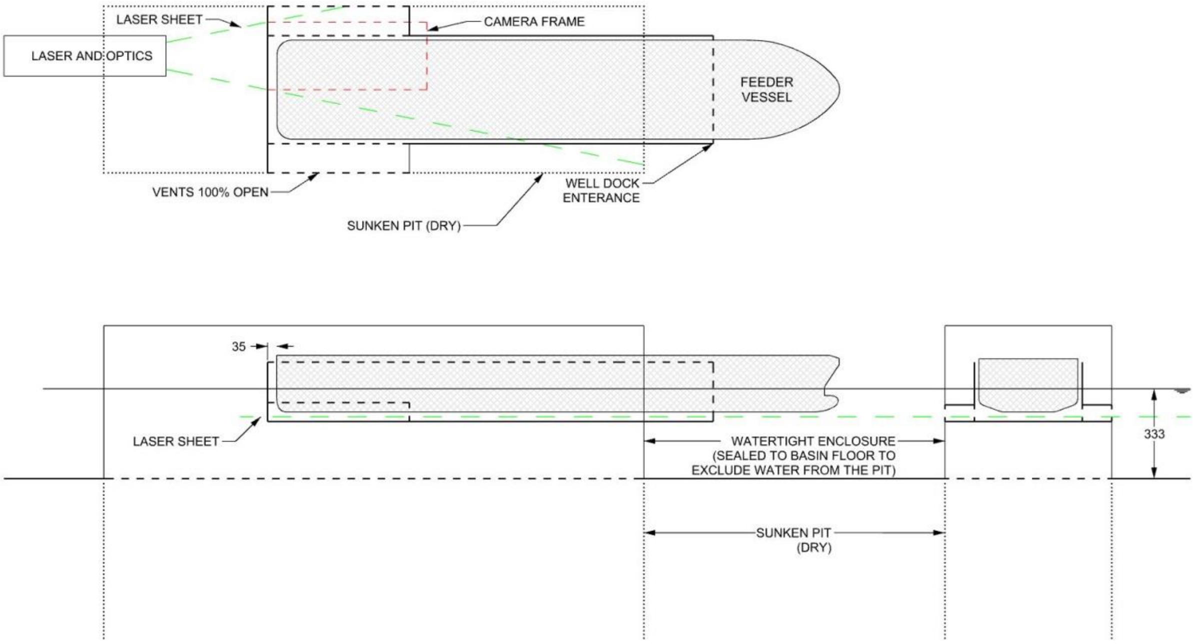

Figure 4.1: Experimental apparatus positioned over the sunken pit showing the feeder vessel in its docked position showing the location of key PIV equipment.

Figure 4.2: Profile view of the well dock (full length) illustrating three of the vent configurations, 100% open (all shaded areas), 50% open (two darker shaded areas) and 25% open (the darkest shaded section). Note: vents were present on both sides of the mothership well dock.

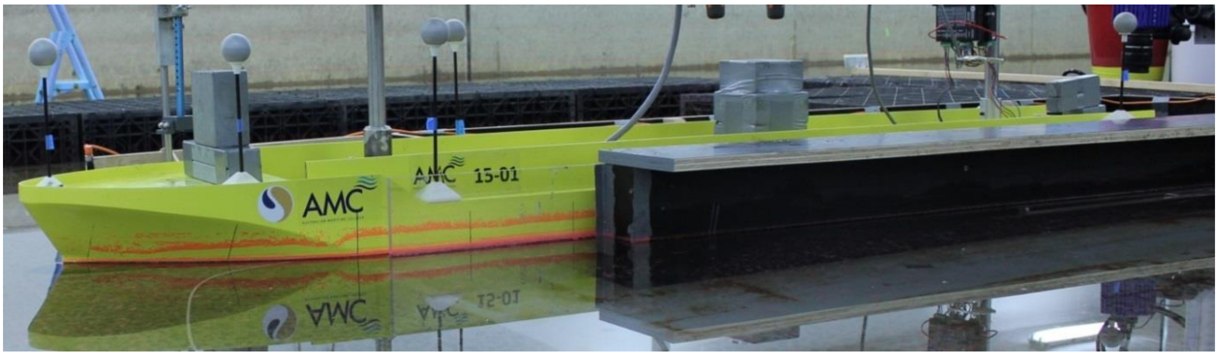

Figure 4.3: Photograph of feeder vessel model docked within the Perspex well dock model. The fluorescing wax particles can be seen accumulating along the feeder vessel near the waterline and a second line slightly higher where the vessel has been heeled over during setup.

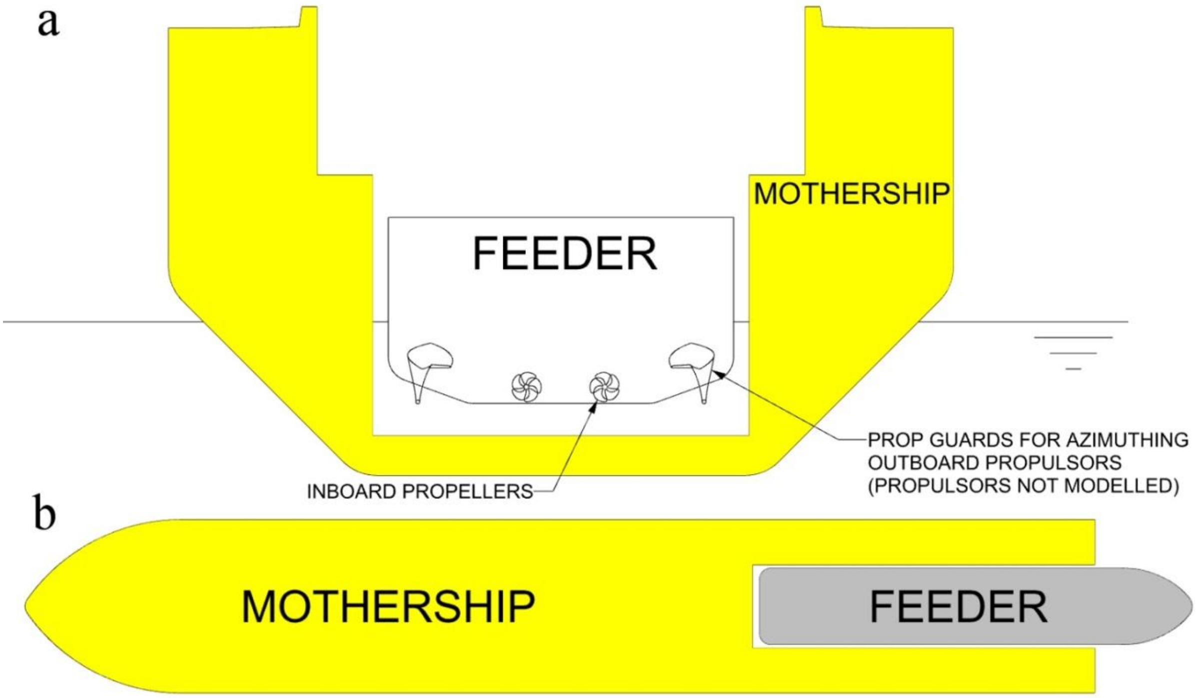

Figure 4.4: Body plan (a) and plan (b) views of the feeder vessel docked in the well dock, demonstrating the relative difference between the feeder vessel and well dock cross sections for the present study. The location of the propulsors and prop guards are also highlighted.

A sunken pit below the concrete floor of the basin was sealed from the ingress of water for this experiment and used to position three mirrors to redirect the view of the camera and one to redirect the path of the laser sheet. These mirrors enabled the camera and laser to be positioned above the water surface removing any requirements for waterproof housings or borescopes and simplifying the optical considerations. A simplified representation of the transom of the mothership was adopted. Comparison with previous experiments showed that this simplification had no measureable effect upon the docking performance of the feeder vessel. The vent opening configuration was altered by means of interchangeable blocks that altered the length of the vent opening as demonstrated in Figure 4.2.

The principal particulars for the feeder vessel and the simplified well dock model are outlined in Table 4.1. As the feeder vessel docks it must displace approximately 10,000 tonnes of water from the well dock (full scale), which represents approximately 55% of the total volume of the well dock. The width of the well dock is 109% of the feeder vessel beam; the length of the well dock is 79% of the feeder vessel length (the entirety of the feeder vessel is not intended to fit within the well dock, just the cargo-carrying portion); and the static water depth to draught ratio within the well dock is 1.4. A photograph of the feeder vessel model docked within the well dock is presented in Figure 4.3 showing the Perspex well dock model terminating between the two AMC stickers on the feeder vessel. The inboard propulsors and outboard prop guards were included on the scale model of the feeder vessel (refer Figure 4.4). The azimuthing outboard propulsors were not modelled due to the complexity of this system.

Table 4.1: Principal particulars of the tested experimental vessel conditions.

	Simplified Well Dock		Feeder Vessel	
	Ship	**Model**	**Ship**	**Model**
LOA [m]	99.00	1.650	125.00	2.083
Beam [m]	24.00	0.400	22.00	0.367
Draught @ LCF [m]			5.19	0.087
Depth in well dock [m]	7.26	0.121		
Displacement [t]			11284	0.051
Trim [degrees]	0	0	0	0
VCG [m]			9.35	0.156
LCG (from transom) [m]			57.81	0.964

The aims of the experiment required as much consistency between comparative conditions as possible and as a result the feeder vessel speed profile was precisely controlled. The three steady-state test speeds of 1.0, 1.5 and 2.0 knots full scale were conducted in both directions for each vent configuration. These speeds were selected as they were considered by the Master Mariners consulted as being realistic for these somewhat unique docking and departure operations. A constant and equal linear ramp rate was applied to all acceleration and deceleration events which resulted in acceleration to the highest steady-state test speed of 2.0 knots in approximately 58% of the well dock length. Whenever reference is made to feeder vessel speed in this chapter it refers to these nominal full scale steady-state speeds of 1.0, 1.5 or 2.0 knots however all flow velocity values remain in model scale as the scale effects associated with a confined flow such as this make transferring these results to full scale impractical early stage of investigation.

The flow velocities obtained using PIV were validated against analytical approximations for flow within the well dock for the no vents condition to ensure that the flow velocities obtained were realistic and good agreement was observed across the range of vessel speeds tested. Flow visualisation and velocity results were compared to flow visualisation tests that were performed using dye injection to further validate the trends being obtained from the PIV measurements.

It should be noted that PIV techniques were applied at this stage of the project to enable objective comparison between vent conditions rather than precise measurement of flow velocities. To ensure the consistency of the data obtained, a number of repeat runs were included across the range of speeds and vent configurations (one speed per configuration was repeated at least twice). The challenges of measuring the flow during slow speed tests is acknowledged and the effect of random error was considered using these repeat runs. Consideration was given to the systematic errors that may also be present within the flow visualisation results and the relative trends observed are believed to be reliable, but caution should be exercised when interpreting absolute physical flow magnitudes from the presented plots.

The water inside the well dock was seeded with custom-made neutrally buoyant fluorescing wax particles each time the feeder vessel was out of the well dock (every two runs) to maintain adequate and consistent seeding. The particles had an approximate size range of 30 – 100 microns and were premixed in a container (~10 litre capacity) prior to being introduced into the test volume to achieve an acceptable seeding density.

The feeder vessel model was free to roll, pitch and heave while being constrained in surge, sway and yaw. PIV images were captured for the entire duration of each run; from a completely stationary condition, the entire period that the feeder vessel was moving through the well dock and for a period following this movement to capture all relevant stages of water flow. The time between two corresponding PIV frames was varied depending on the vessel speed and thus the expected flow velocity, interframe time intervals varied between approximately 10 and 20 milliseconds and the capture rate of PIV image pairs was 25 Hz. Four vent configurations were investigated; vents 100% open, vents 50% open, vents 25% open and no vents; and for each vent configuration the docking and departure manoeuvres were performed at each of the three nominated feeder vessel speeds. The primary measurements for this experiment were the PIV images to visualise and quantify the flow within the well dock. The plane on which the flow was measured was one quarter of the well dock vent height above the well dock floor. This is midway between the underside of the feeder vessel keel and the well dock floor when the feeder vessel is docked and stationary. This position is expected to give a good indication of the dominant influences on the flow field and provides a good foundation on which to build an understanding of the flow within the well dock. The camera frame covered half of the width of the well dock (it was assumed the geometric symmetry of the experiment would result in symmetrical results about the centreline) and extended from the end wall of the well dock to a small distance aft of the largest vent opening as shown in Figure 4.1.

Other data sets were recorded to ensure consistency with previous investigations, including the heave motion, pitch motion and longitudinal force experienced by the feeder vessel. The speed of the feeder vessel model was measured using the speed control unit linked to the electric drive motor. Its position was also monitored using a Qualisys digital video motion capture system covering the full range of motion as well as a linear displacement sensor with a range of 1.5 m for the transit through the well dock where the precise position was desired.

4.3 Results and discussion

Image processing techniques provided within the LaVision DaVis software were used to analyse and quantify the flow field within the well dock. A single and consistent feeder vessel position (where the vessel was at the steady-state speed) was analysed from each scenario to ensure that any variation in the observed flow field was due to either the approach speed or the vent configuration. Sensitivity studies were performed on the image processing parameters to ensure the highest level of accuracy. Once selected, the image processing parameters remained consistent for all analysis. No data smoothing or filling was performed as this was deemed unnecessary for this application and could mask some features of the flow field. The flow field for each run and the four vent configurations were compared for both the docking and departure manoeuvres. The plane on which the flow field is presented is halfway between the underside of the feeder vessel and the well dock floor and in all flow field images the feeder vessel outline has been superimposed to demonstrate its position within the well dock.

The first series of results presented and discussed (Figures 4.5 to 4.10) are taken at the point in time when the feeder vessel is 70% docked (NB: 100% indicates the feeder vessel is in the fully docked position, as described in Section 2, while 0% is when the transoms of the feeder vessel and mothership are level). The docking case, where the feeder vessel enters the well dock stern first, is presented in Figure 4.5 (1.0 knots), Figure 4.6 (1.5 knots) and Figure 4.7 (2.0 knots). Similarly, the results for the departure case (exits bow first) are presented in Figures 4.8 to 4.10.

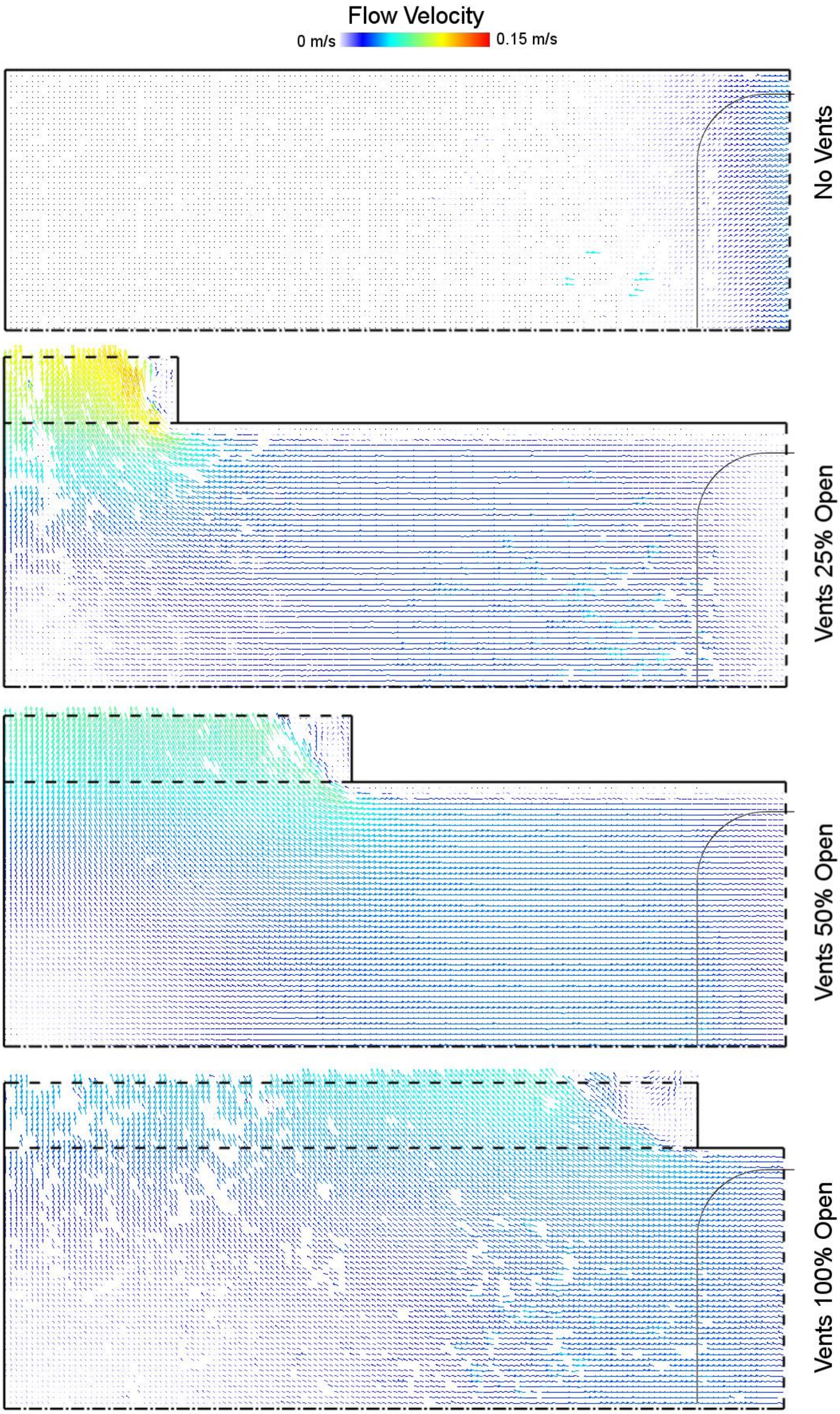

Figure 4.5: Flow visualisation for the feeder vessel docking across each of the 4 vent configurations for the docking manoeuvre at the steady-state speed of 1.0 knots. The outline of the feeder vessel stern is shown to indicate feeder vessel position.

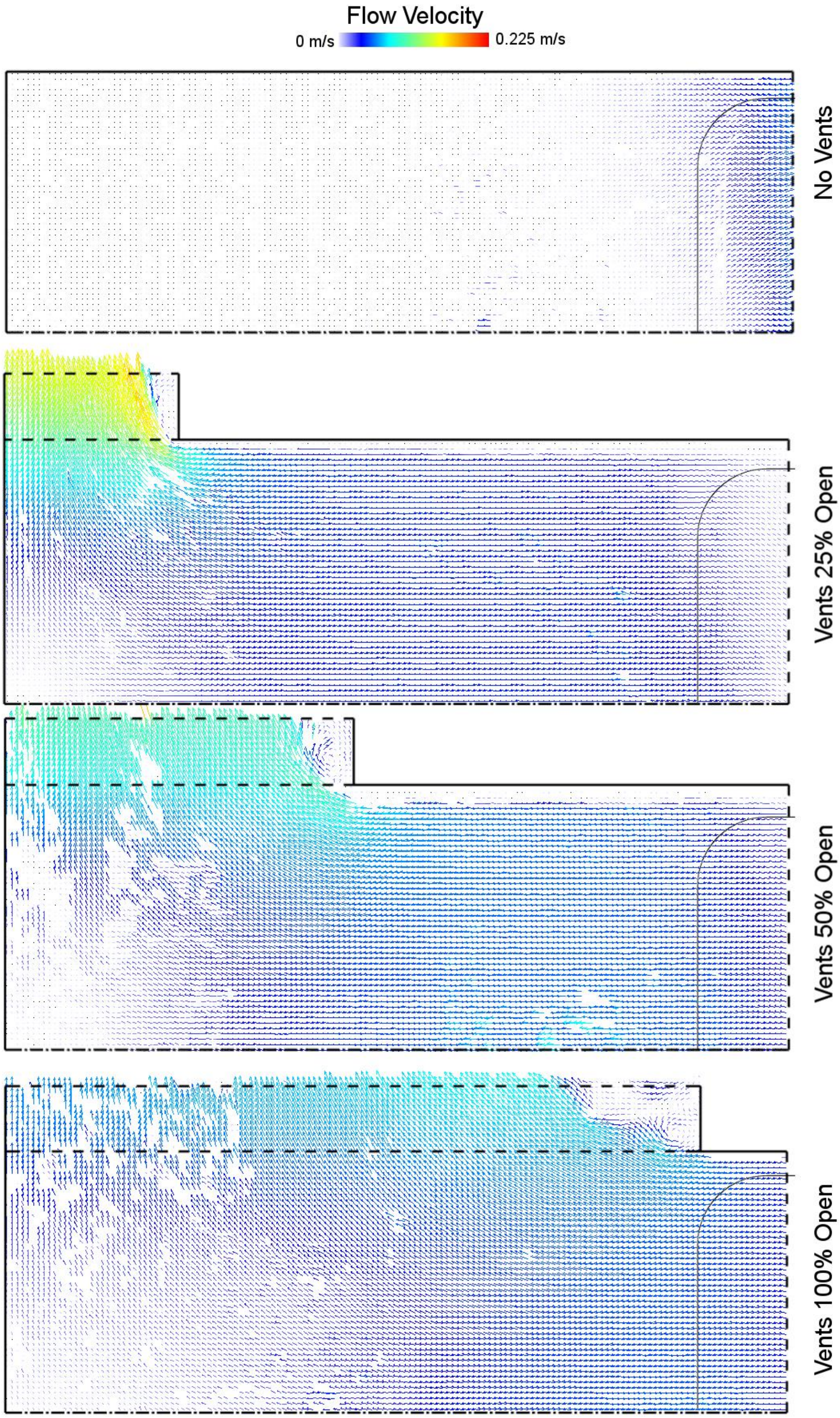

Figure 4.6: Flow visualisation for the feeder vessel docking across each of the 4 vent configurations for the docking manoeuvre at the steady-state speed of 1.5 knots. The outline of the feeder vessel stern is shown to indicate feeder vessel position.

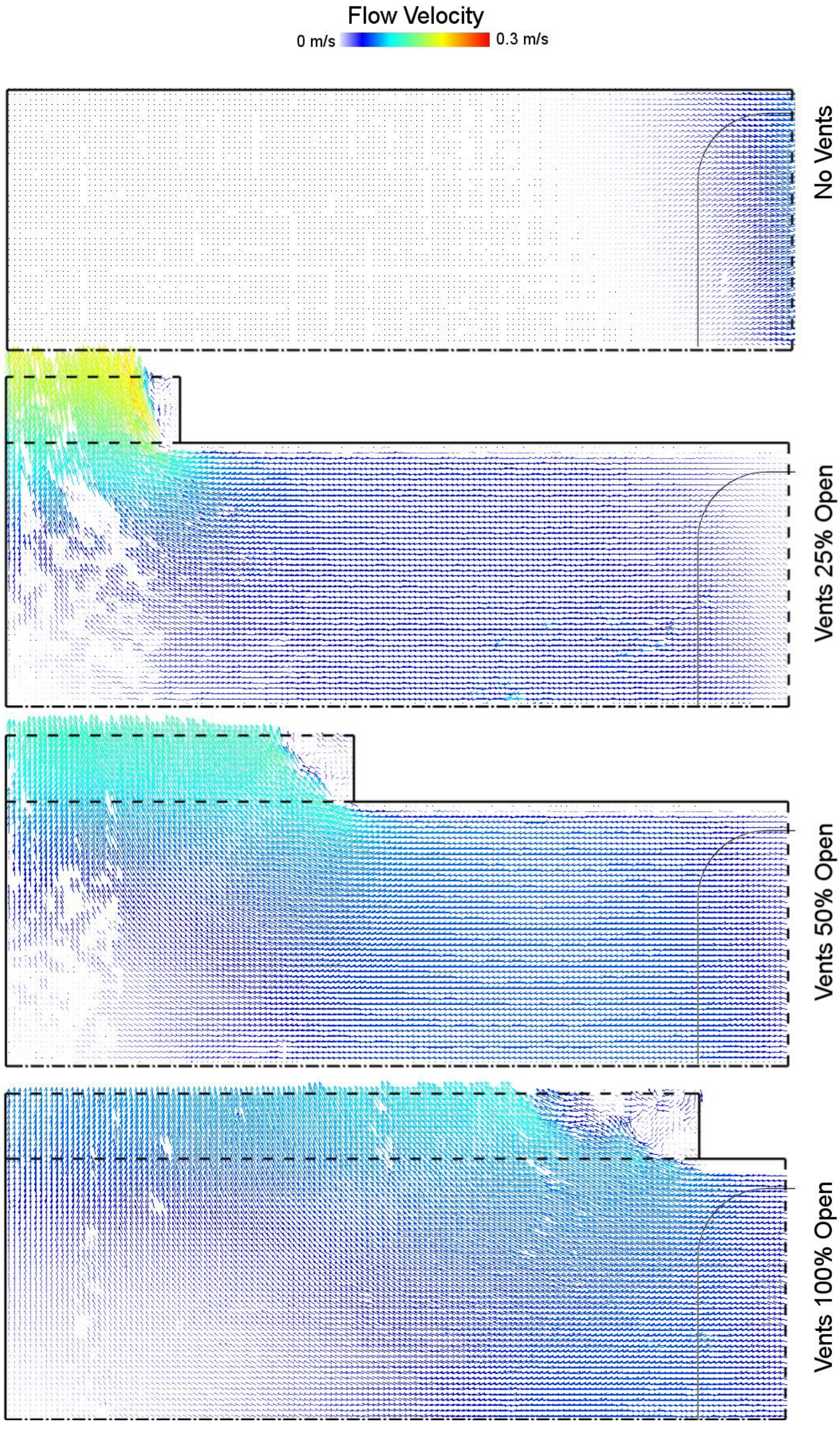

Figure 4.7: Flow visualisation for the feeder vessel docking across each of the 4 vent configurations for the docking manoeuvre at the steady-state speed of 2.0 knots. The outline of the feeder vessel stern is shown to indicate feeder vessel position.

Figure 4.5 shows the flow field that exists for each of the four vent configurations when the feeder vessel docks at 1.0 knots. There is a stark contrast in the results for the three cases that include vents compared to the sole case where there are no vents. Interestingly, there are significant similarities between the three cases with vents, with a gradual reduction in flow velocities close to the vent as vent size increases. This is expected given the increased area for water to escape the well dock with a large vent. It is interesting to note that the only flow of measurable significance within the no vents configuration was confined to the region immediately beneath the feeder vessel where there is an even outward flow across the full width of the well dock. For the vents 25% open case the water particles in this same region were all but stationary indicating that the bulk of the water escaping the well dock was now flowing through the open vent, as intended. The vents 50% and 100% open configurations show reduced flow velocities through the vent but also a low velocity flow moving inwards (with the feeder vessel) through the well dock entrance which increases with increased vent opening. This inward flow is consistent with the viscous effects surrounding the feeder vessel and indicates that the PIV plane could be passing through the boundary layer of the feeder vessel. There is a region in the centre of the well dock near to the end wall that exhibits nearly zero flow velocity across all vent configurations. The area of this region was smallest for the vents 25% open configuration and grew with increased vent opening. This region is most likely stagnant due to its location within the well dock and the symmetrical nature of the flow field.

Figure 4.6 presents the flow field comparison for each of the four vent configurations for the slightly faster docking approach speed of 1.5 knots, which shows strong similarities to the results for the 1.0 knots approach speed. The primary difference to the slower approach speed is that the observed flow speeds have increased for all vent configurations and the flow is slightly more consistent. Again, the flow direction beneath the feeder vessel is outward for the no vents configuration, negligible for the vents 25% open configuration and inward for the vents 50% and 100% open configurations. The flow velocity through the vent again decreased with increased vent opening and the region of near zero flow at the centre of the end of the well dock was consistent with the 1.0 knots approach speed condition.

Similarly, flow visualisation for the 2.0 knots approach speed is presented in Figure 4.7. This shows very comparable trends to the 1.0 and 1.5 knots docking speeds. Flow speeds again increase proportionally to the docking approach speed and the 25% open vent causes very little flow to occur through the well dock entrance. As the vent size is increased further, water begins to enter the well dock through the entrance and gains velocity with increased vent size.

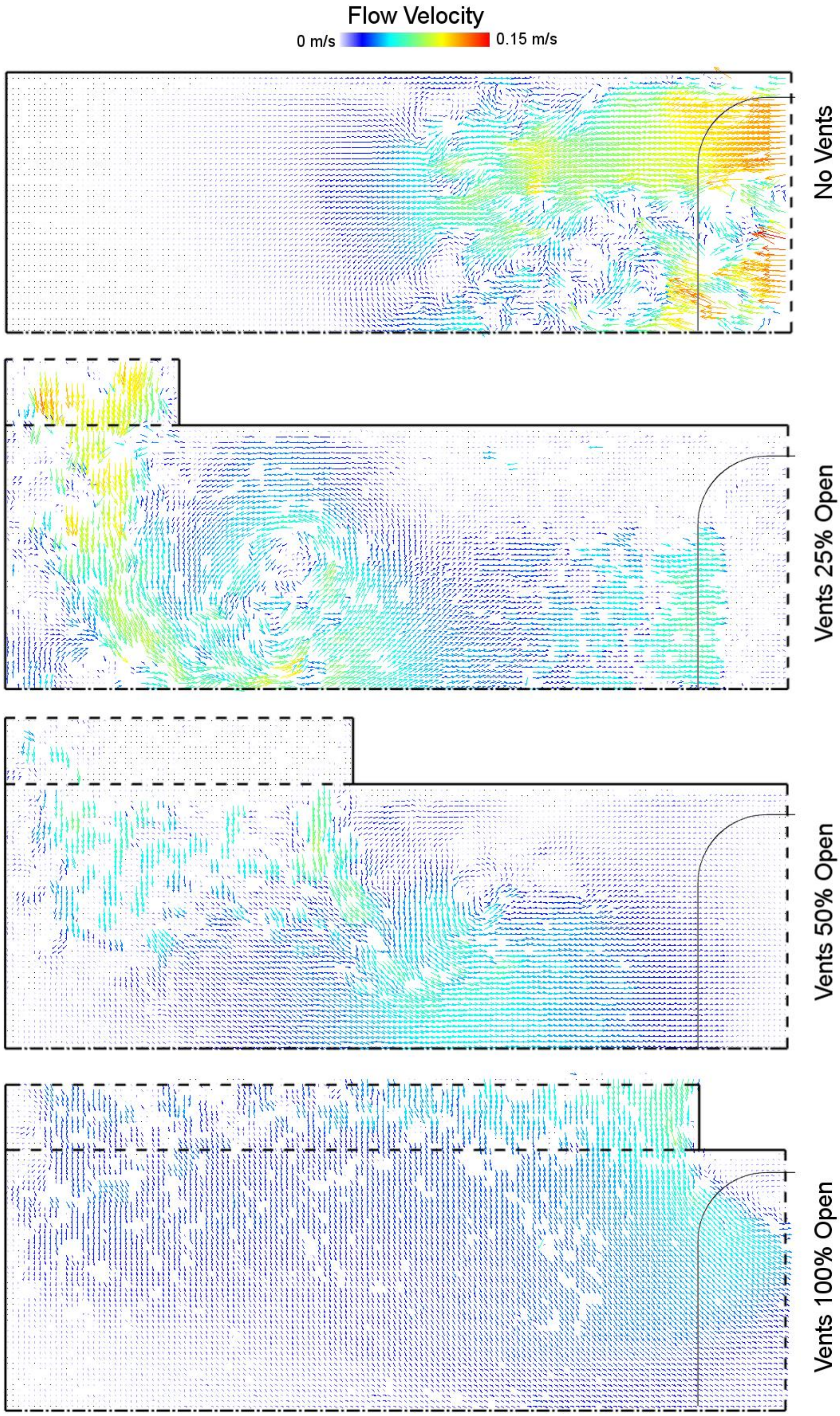

Figure 4.8: Flow visualisation for the feeder vessel departing across each of the 4 vent configurations for the docking manoeuvre at the steady-state speed of 1.0 knots. The outline of the feeder vessel stern is shown to indicate feeder vessel position.

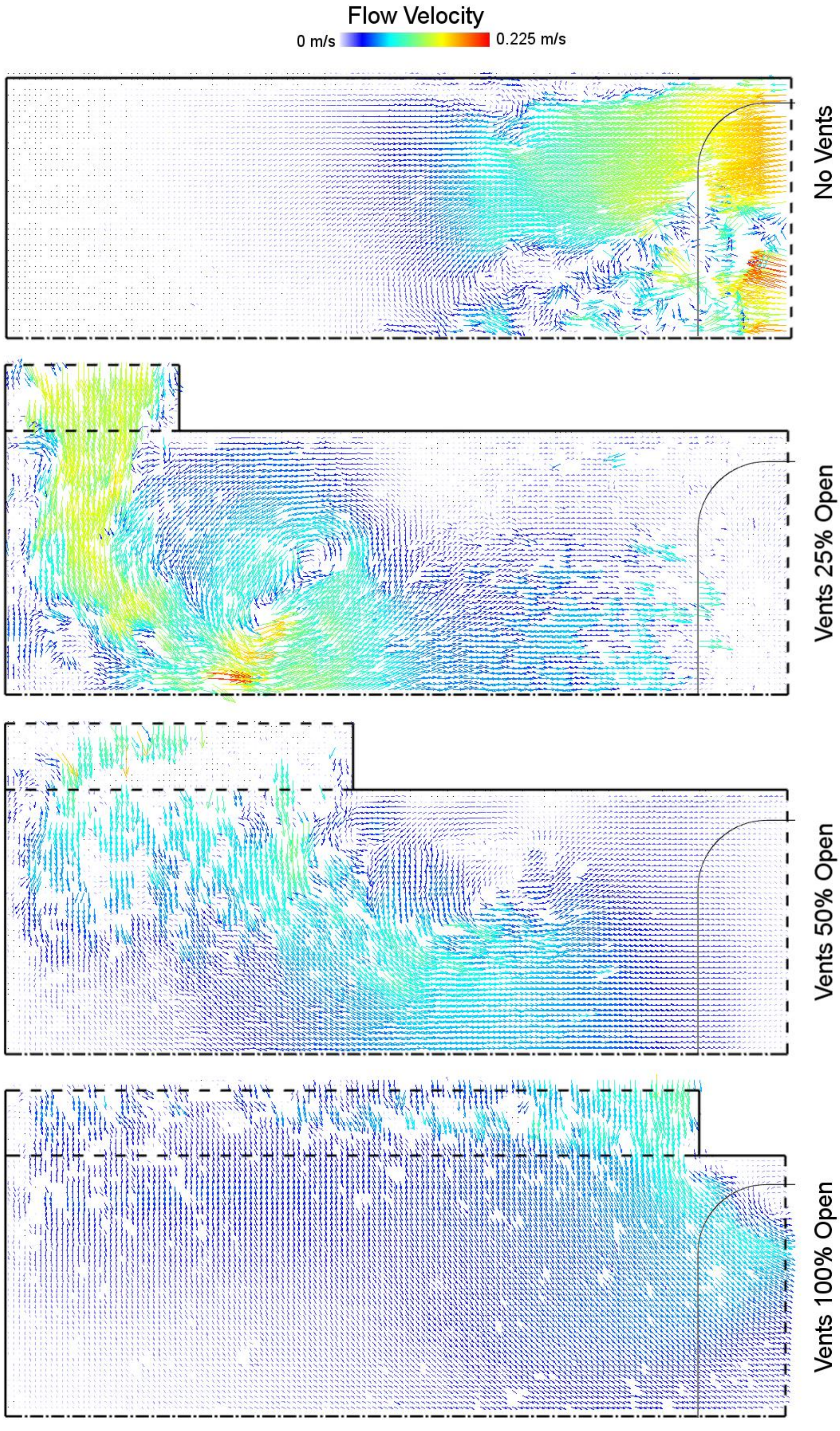

Figure 4.9: Flow visualisation for the feeder vessel departing across each of the 4 vent configurations for the docking manoeuvre at the steady-state speed of 1.5 knots. The outline of the feeder vessel stern is shown to indicate feeder vessel position.

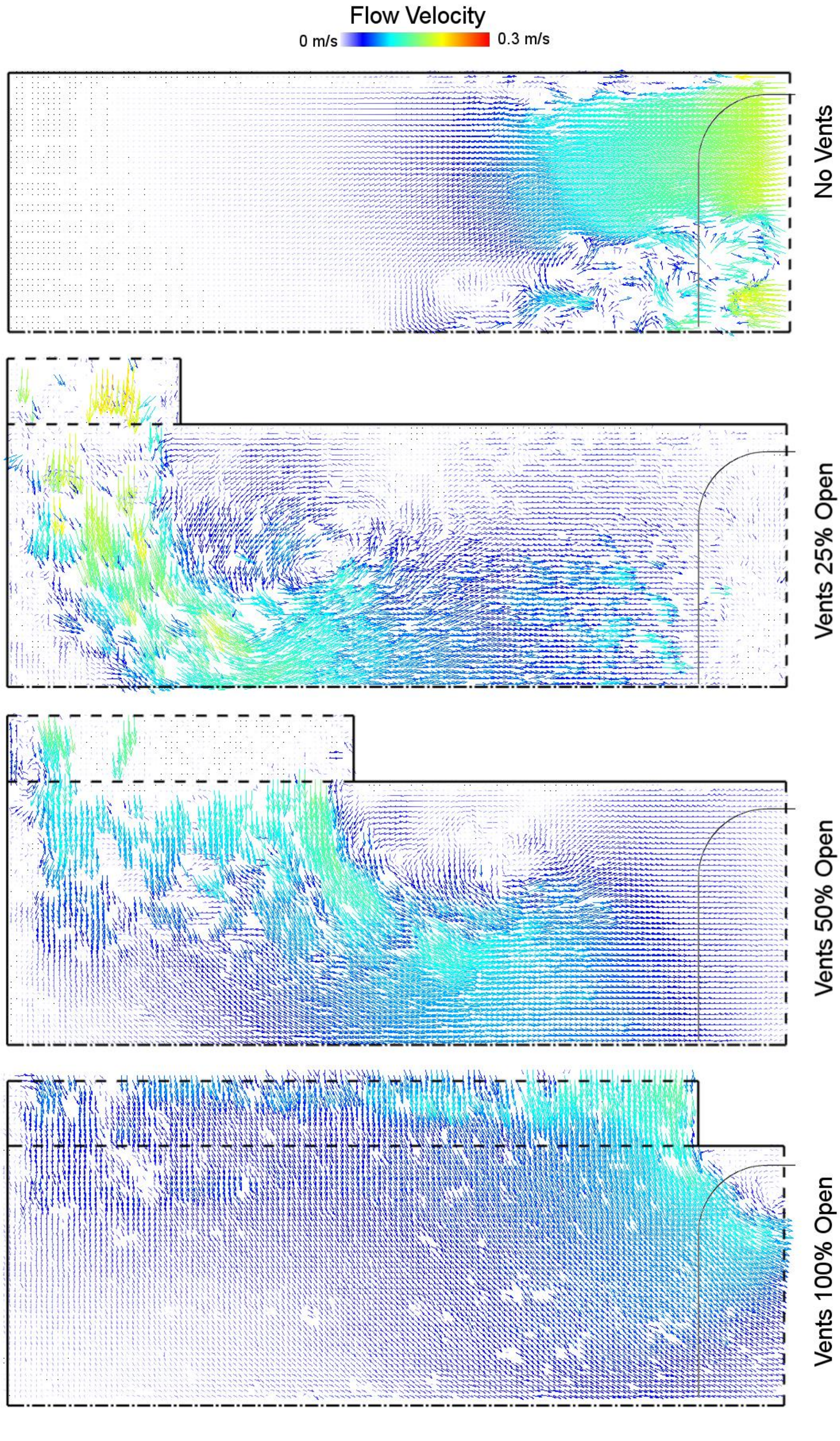

Figure 4.10: Flow visualisation for the feeder vessel departing across each of the 4 vent configurations for the docking manoeuvre at the steady-state speed of 2.0 knots. The outline of the feeder vessel stern is shown to indicate feeder vessel position.

The same process was undertaken for the outbound departure manoeuvre (for the same three speeds) with the flow analysed at the same longitudinal location as for the docking manoeuvre using the same image processing parameters. While there was no significant change in flow field trends within the well dock across the three vessel speeds during the docking manoeuvre, this was not the case for the departure manoeuvre. It was also found that more care and effort was required to maintain adequate seeding within the region of interest, as less densely seeded water was drawn into the well dock through the vents during the outbound runs. This yielded flow field measurements that occasionally appear patchy due to areas of lower particle density. This was found to be most problematic for the vents 50% open condition.

Figure 4.8 presents the flow field within the well dock for each of the four vent configurations for the 1.0 knots steady-state departure speed. The no vents configuration yields a large region of negligible velocity at the innermost end of the well dock. A strong and reasonably linear inflow was observed on the outside quarter of the well dock width along with a confused flow that trends inwards in the centre half of the well dock. These regions indicate that fluid is flowing around and beneath the feeder vessel to fill the void created by its departure, but this inflow is interacting with the boundary layer of the feeder vessel close to its centreline where the under keel clearance between the vessels is smallest.

For the vents 25% open configuration, a region of almost stationary flow is observed beneath the stern of the feeder vessel in a similar manner to the corresponding configuration during the docking manoeuvre. The flow entering the well dock through the vent appears to have significant momentum, demonstrated by the fluid vectors remaining perpendicular to the feeder vessel motion before interacting with the flow from the opposite side vent. This causes the water entering from each vent to swirl before following the feeder vessel as it departs through the well dock entrance. There is a small region of circulating flow present in the outside quarter of the well dock just in front of the vent as most of the flow towards the entrance is through the centre half of the well dock indicating that the inertial properties of the fluid play a significant role in the measured flow. When the vent size is increased to 50% open the peak velocity of the flow through the vent decreases and the flow across the vent becomes more even. The vortex observed due to the fluid momentum becomes less pronounced and moves aft and slightly outwards. Further widening of the vents to 100% open yields a flow pattern that is more uniform and very similar, but reversed, to the flow pattern that is observed when the feeder vessel is docking for the corresponding vent case.

When the steady-state departure speed is increased to 1.5 knots (see Figure 4.9) there are significant similarities with the behaviour observed for the 1.0 knots departure case. As for the inbound direction, the no vents condition yields a slightly more consistent flow at 1.5 knots. This trend continued for the vents 25% open condition where the increased flow velocity leads to greater definition of the vortex. When the vents are 50% open, the flow field displays a slightly stronger longitudinal flow pattern, but the flow pattern continues to look very similar to the corresponding configuration at 1.0 knots. A similar result is also found once the vents are fully open.

The flow field results for the highest departure speed investigated are presented in Figure 4.10. Not surprisingly, the complex flows observed at the slower speeds for the no vent and 25% open vent cases are even more pronounced at 2.0 knots due to the increased velocities involved. The flow behaviour is more consistent, particularly for the no vents condition. The vortices observed in the 25% and 50% open vent conditions were found to be not as tight as the slower speed equivalents due to the increased fluid momentum.

Up to this point only the fluid flow pattern at a single moment in time (feeder vessel position) during the docking and departure manoeuvres has been investigated. This approach was adopted to isolate the effect of the vent opening on the flow field within the well dock during feeder vessel manoeuvres. These results demonstrate significant differences between the no vent and the open vent conditions (particularly 25%). This is in agreement with the findings of Chapter 3 which explored the feeder vessel motions and longitudinal force during the same manoeuvres. The logical extension is to expand the investigation from a single (common) feeder vessel position to several longitudinal positions (time-steps) along the length of the well dock. To investigate the flow development behaviour, a series of four snapshots are interrogated over the period of the feeder vessel moving through the camera frame. The four feeder vessel positions investigated are 93%, 84%, 75% and 66% docked. Although all three feeder vessel speeds and four vent configurations were investigated for each of the docking and departure cases, only a select few cases are presented here to demonstrate flow development behaviour during the feeder vessel manoeuvres. The no vent and vents 25% open configurations at the single steady-state docking/departure speed of 1.0 knots were selected due to the stark differences observed between them in the preceding analyses.

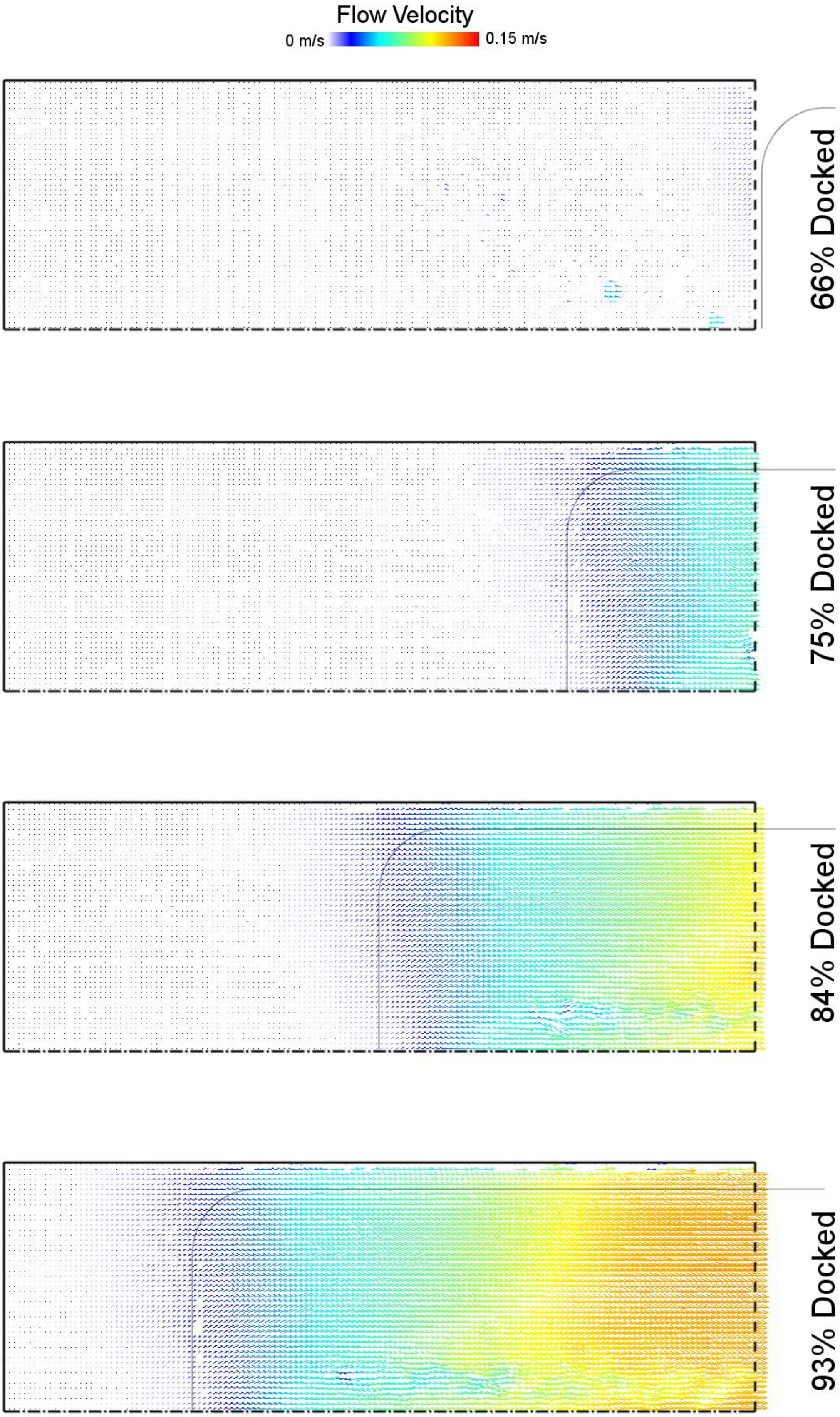

Figure 4.11: Flow development during the docking manoeuvre at 1.0 knots with no vents for 66% docked 75% docked, 84% docked and 93% docked.

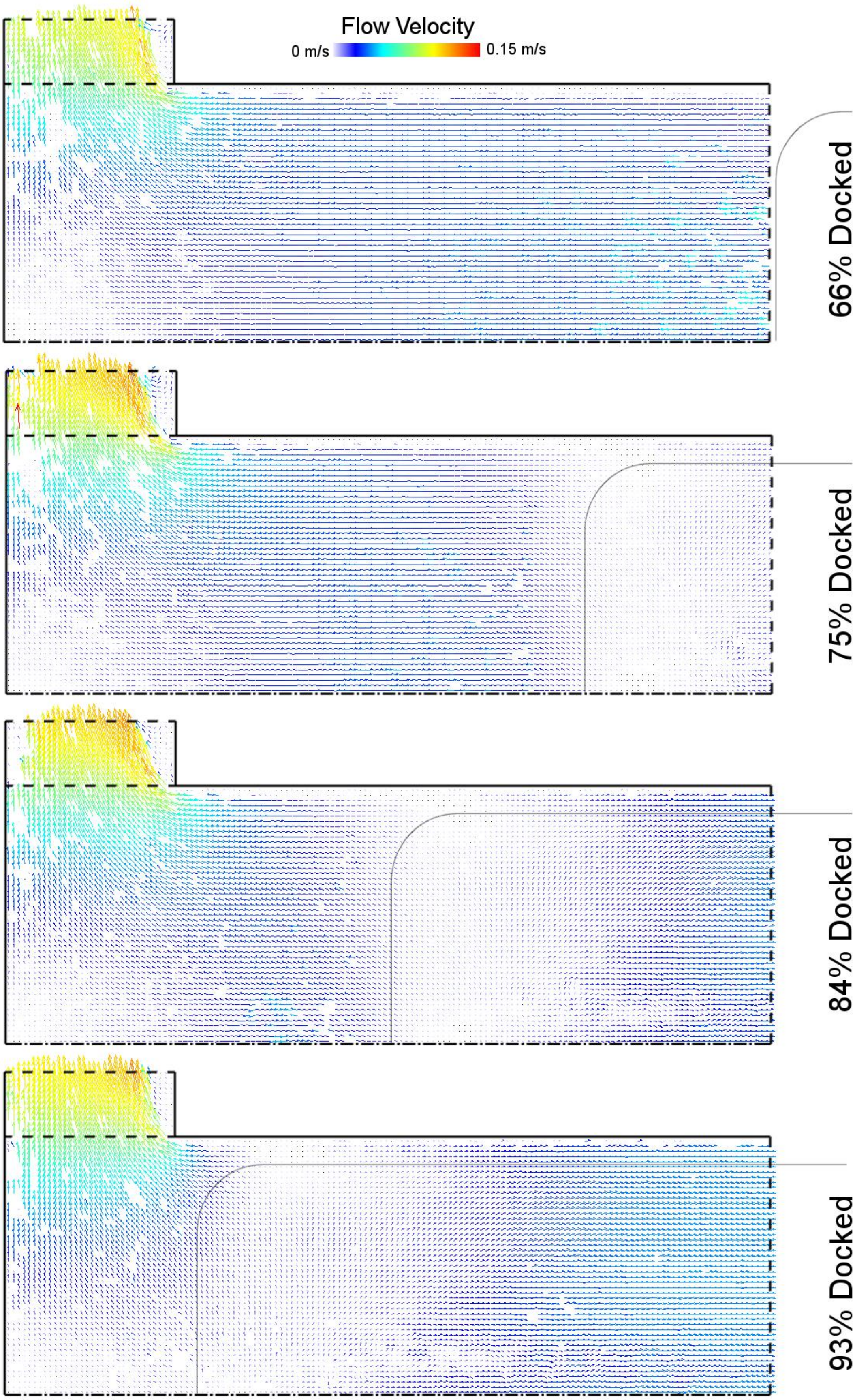

Figure 4.12: Flow development during the docking manoeuvre at 1.0 knots with the vents 25% open for 66% docked, 75% docked, 84% docked and 93% docked.

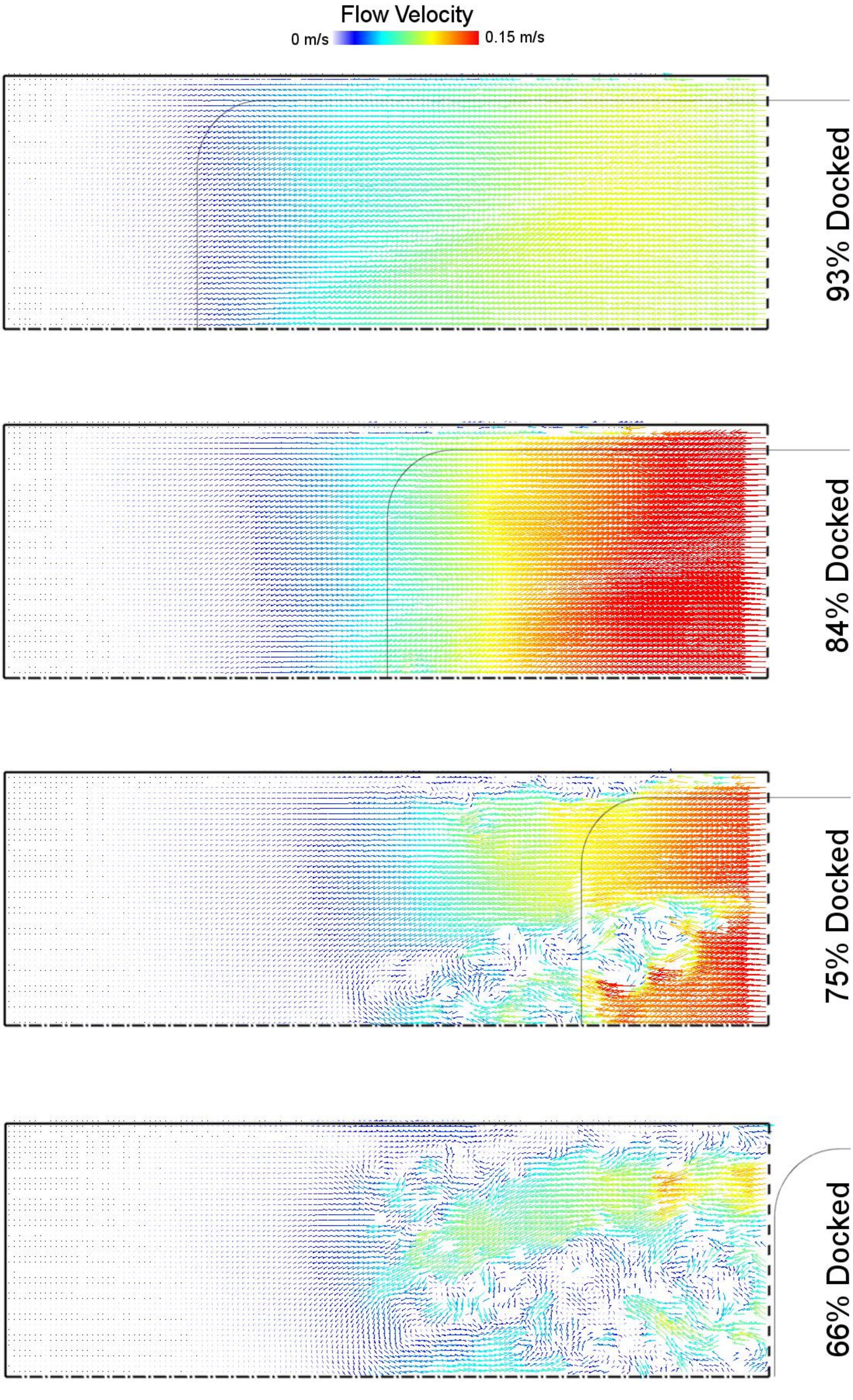

Figure 4.13: Flow development during the departure manoeuvre at 1.0 knots with no vents for 93% docked, 84% docked, 75% docked and 66% docked.

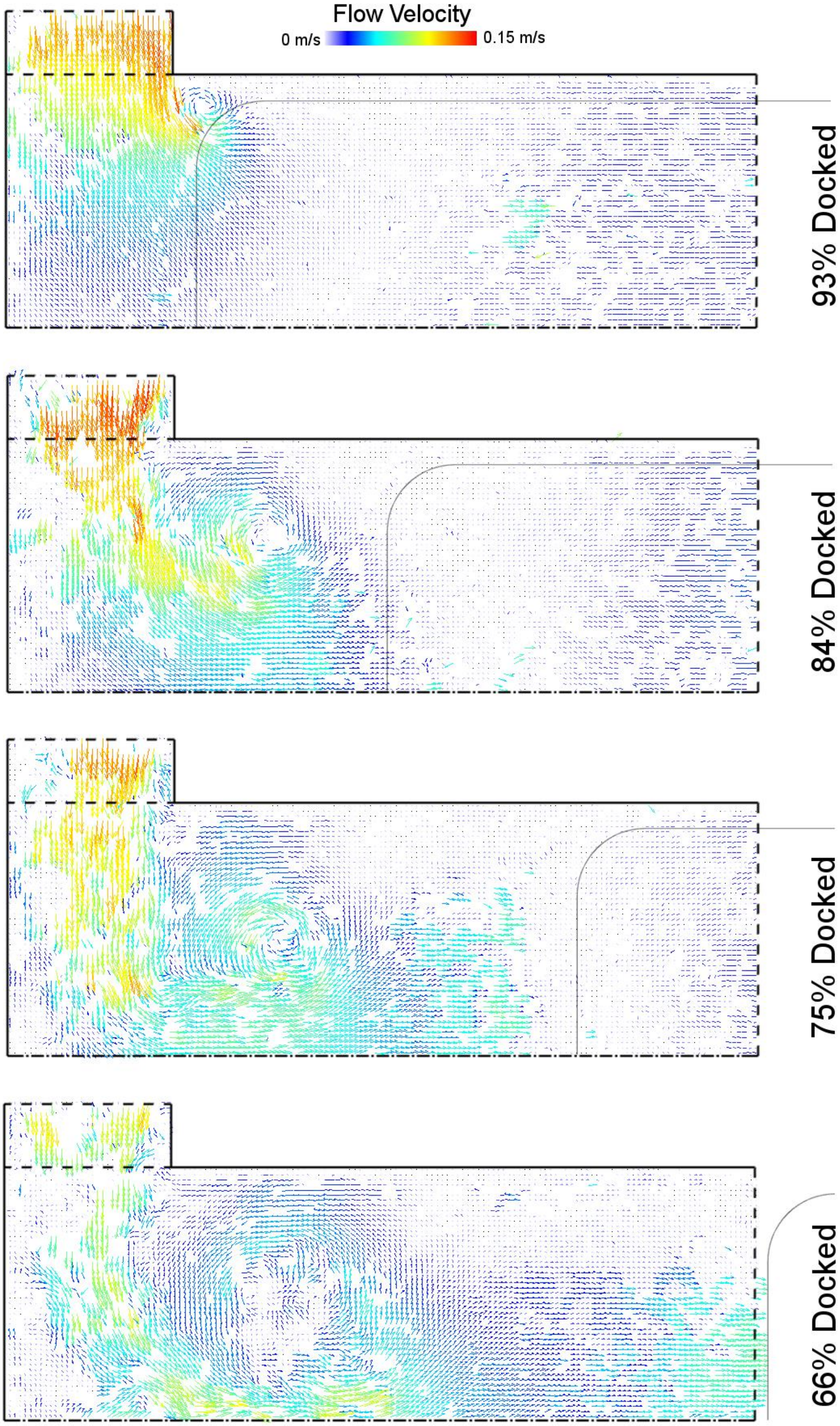

Figure 4.14: Flow development during the departure manoeuvre at 1.0 knots with the vents 25% open for 93% docked, 84% docked, 75% docked and 66% docked.

The flow development for the feeder vessel docking at 1.0 knots into a well dock with no vents is shown in Figure 4.11. At a feeder vessel position of 66% docked there is almost zero flow recorded within the capture frame, but as it moves further into frame (at a position of 75% docked) there is a very even outflow under the vessel, beginning close to the transom. Although the flow velocity appears to be relatively constant transversely across the feeder vessel width, it is clearly increasing along the vessels length (lowest at the transom). There is little change in these trends as the vessel moves to 84% docked, but there is a small region of disturbed flow on the lower edge of the flow field image. The start of this disturbance closely aligns with both the transverse and longitudinal locations of the (stationary) propulsor that was fitted to the feeder vessel model (refer Section 4.2). The final image in the series presents the feeder vessel as it approaches its docked position (93% docked) where the outward flow velocity beneath the feeder vessel clearly increases the closer it gets to the well dock entrance. In this image the disturbance attributed to the propulsor is clearly visible for most of the visible feeder vessel length.

The flow development during feeder vessel docking at 1.0 knots for the vents 25% open condition is presented in Figure 4.12. There is no significant variation in the flow field as the docking manoeuvre progresses, however the region of near zero flow remains beneath the stern of the feeder vessel throughout the manoeuvre. Comparing these results to those presented in Figure 4.11 confirms a dramatic effect on the flow behaviour due to the inclusion of (25% open) vents to permit water to flow out of the well dock as the feeder vessel docks. Importantly, there is a notable reduction in flow velocity around the stern of the feeder vessel for the vents 25% open case, which is expected to improve the effectiveness of the propulsors, hence also controllability of the feeder vessel.

The same comparison was performed for the feeder vessel departure manoeuvre, as presented in Figure 4.13 and Figure 4.14 for the no vents and vents 25% open cases respectively. When there are no vents and the feeder vessel has just begun to depart (93% docked), an even inward flow quickly develops across the width of the well dock beneath the feeder vessel, increasing in velocity along its length, and there is negligible flow aft of the feeder vessel. As the feeder vessel progresses to 84% docked, most of the water in the region aft of the feeder vessel remains quite stationary with a small region of outward flow close behind the feeder vessel. Underneath the feeder vessel experiences very high inward flows due to the quantity of water that is rapidly entering the well dock to fill the void created as the feeder vessel departs. The maximum flow velocity recorded in this region was more than 2.5 times the steady-state departure speed of the vessel. When the feeder vessel has reached the 75% docked position, there is a flow disturbance that originates from the propeller guard of the outboard propulsors (the propeller guards are modelled even though the outboard propellers are not). This region of mixed flow increases in size as the feeder vessel reaches the 66% docked position and the only region of consistent flow is aft of the feeder vessel on the outboard edge of the well dock and flowing towards the centre of the well dock. The region of negligible flow remained quite consistent in size and position from the 84% docked position through until the feeder vessel leaves the frame.

The introduction of vents to the well dock again completely alters the flow characteristics for the departure case at 1.0 knots (Figure 4.14). When the vents are 25% open the flow field is seen to again develop quickly for the departure manoeuvre with a strong inflow through the vent observed when the feeder vessel reaches the 93% docked position. This inflow dissipates upon entry to the well dock and loses most of its velocity within a quarter of a feeder vessel beam from the vent. When the feeder vessel reaches the 84% docked position, the vortex observed during the 1.0 knots departure with 25% and 50% open vents (Figure 4.8) starts to form slightly aft of the feeder vessel transom. The region underneath the feeder vessel has a small flow velocity throughout the time that the feeder vessel is in the capture frame. When the feeder vessel is 75% docked the flow field further develops to include a region of steady outbound flow along the centreline of the well dock aft of the feeder vessel. The vortex also begins to move slightly towards the centreline. At the next feeder vessel position (66% docked), the vortex has expanded and reduced intensity and the steady region of outbound flow along the centreline begins to dominate.

Comparison of the flow development between the no vents and the vents 25% open configurations shows that the introduction of the vents reduces the effect from the well dock being enclosed at one end. During docking, the feeder vessel with 25% open vents indicates that there are still some confined water effects under these conditions. These generalised outcomes suggest that the vents 25% open option is close to reaching a balance between mitigating the effects of a closed well dock and the potential increase in relative motions when in a seaway, as considered in the related seakeeping study.

4.4 Broader implications

Feeder vessel manoeuvring will be safest and most effective when the propulsors are working most efficiently and the feeder vessel is subjected to minimum external disturbing forces. Some of the possible disturbing forces to be minimised are those generated when operating in confined water – with or without a seaway. When in a seaway, the impact of incident waves and swell is reduced due to the sheltering effect provided by the mothership, with the greatest benefit observed when the vent size is reduced (or there are no vents). Other external disturbing forces could be due to variable or unequal flow around the feeder vessel and its propulsors. The most variable flow around the propulsors in terms of controllability was observed during the docking manoeuvre when there were no vents. Operational conditions significantly improved when vents were introduced indicating that vents are beneficial to feeder vessel operations. The propulsors will perform best when subjected to consistent flow opposite to the motion of the vessel. There were no instances observed where the flow over the propulsors was significant and in the direction of travel of the vessel. In more open vent configurations where there was negligible flow under the aft section of the feeder vessel, the propulsors are expected to behave similar to operations in open water. When no vents were present very high flow velocities in the opposite direction to feeder vessel motion were observed, causing increased thrust requirements and decreased propulsor effectiveness. These findings support the inclusion of the vents in the well dock.

It was noted that the inclusion of the vents caused a jet like flow (particularly at higher feeder vessel speeds and smaller vent openings) to exit the vents during feeder vessel docking. This flow through the side of the mothership could potentially interact with an ocean going vessel if one were moored alongside. While this is outside the scope of this preliminary investigation, it is expected that this will have no significant influence based on the proposed hull form of the mothership (refer Figure 4.4).

The docking and departure of the feeder vessel may be influenced by an incident seaway under real world conditions. Now that a good understanding of a baseline case in calm water has been obtained, it is feasible to expand the investigation into docking and departure in a sea state. This may re-introduce the possibility of impact between the vessels during docking and departure and add another dimension to the vent sizing considerations.

4.5 Concluding remarks

An experimental campaign has been undertaken to investigate a feeder vessel entering/departing a well dock whose cross section is only slightly larger than the feeder vessel. The focus of this investigation was on the collection and analysis of flow field data within the well dock of the mothership using 2-dimensional PIV. The docking (feeder vessel moving astern into the well dock) and departing (feeder vessel moving ahead as it exits the well dock) manoeuvres were investigated at speeds of 1.0, 1.5 and 2.0 knots full scale. The effectiveness of well dock vents for mitigating the effects of the confined well dock was determined by comparing three different vent configurations and the base case with no vents.

During the docking manoeuvres a large region of zero (or very low) flow velocity was observed at the enclosed end of the (unvented) well dock. When vents were introduced there was an obvious and generally consistent flow throughout the well dock. During departure the same trend was apparent whereby the no vents configuration caused a region of zero (or low) flow velocity at the end of the well dock and the inclusion of vents led to flow throughout the well dock. The flow became less disturbed as the vent opening was increased. These observations confirmed that the inclusion of well dock vents is very beneficial for the flow within the well dock, potentially leading to a more uniform flow field within the well dock.

There was a stark difference between the no vents and the smallest vent size investigated (25% open) indicating that while the inclusion of vents was most certainly favourable, they did not need to be large to mitigate most effect of the enclosed well dock. A comparison of the flow development between no vents and 25% open vents showed that this minimal vent configuration was sufficient to mitigate the effects of the single ended well dock when the feeder vessel was departing. There was still seen to be significant flow velocity underneath the mid body of the feeder vessel during the docking manoeuvre.

This initial flow field investigation leads to the conclusion that it is possible to reach a compromise between the docked seakeeping and the docking/departure performance of the feeder vessel. This compromise is that there must be a vent included to mitigate the effects of the well dock but a small vent is sufficient to reduce these effects.

CHAPTER 5

Conclusions and Further Work

5.1 Key Conclusions

This research has explored the hydrodynamics associated with two key operational scenarios that are crucial to the success of the FHT concept; the materials transfer phase and the docking and departure manoeuvres where the feeder vessel moves into and out of the well dock. The well dock that gives the FHT its advantage over other transhipment methods generates a number of unique hydrodynamic phenomena that require deeper investigation. Two key questions surrounding the effect of the well dock and well dock vents on the docked seakeeping and docking/departure manoeuvres have been answered after undertaking three independent experimental programs.

It has been demonstrated that the feeder vessel exhibits notably improved seakeeping performance when it is docked within the well dock as compared to open water operations. This in conjunction with previously published findings highlight that the FHT concept boasts an increased weather window compared to traditional transhipment methodologies. This is further supported by findings that prove the introduction of the well dock has negligible effect on the seakeeping performance of the mothership and docking the feeder vessel inside the well dock also has very little effect on seakeeping performance. This highlights that if the structural considerations surrounding the well dock are satisfied then there is minimal disadvantage to the mothership of including the well dock while delivering a significant improvement to the seakeeping performance of the feeder vessel. The wave environment within the well dock, without the feeder vessel present, was monitored as well dock vents were introduced and it was confirmed that increased vent size leads to increased energy transmission into the well dock.

The relative motion between the vessels was identified as a key indicator of docked seakeeping performance as this is a primary influence on the operational envelope of the materials handling equipment as well as defining contact between the vessels. The relative motion between the two vessels indicates that contact was only likely to occur for very long incident wave periods when no vents are present. The introduction of the 100% open vents was found to negatively influence the feeder vessel motions but have little influence on the mothership. This increase in feeder vessel motions translates to a significant increase in the relative motion between the vessels. Intermediate vent sizes were also investigated and a correlation was found between increased vent size and increased feeder vessel (and relative) motion. Overall, from a purely docked seakeeping point of view, well dock ventilation was concluded to be unfavourable.

A second experimental program was undertaken to investigate the influence of the well dock on the feeder vessel during docking and departure manoeuvres in calm water. Once a baseline performance had been determined, the effectiveness and necessity of the vents could be quantified. The longitudinal force, trim and sinkage of the feeder vessel were identified as the key performance indicators of docking performance and comparison of these parameters between open water transit and well dock manoeuvring confirmed a distinct influence due to the confined water scenario of the well dock. The feeder vessel experienced a significant increase in longitudinal force and was seen to trim down by the bow and the slight bodily sinkage observed in open water disappeared as it moved astern into the well dock (without vents). The bow down trim and lack of bodily sinkage are in opposition to the expected behaviour indicating that the enclosed well dock cause counterintuitive confined water behaviour. While departing, the feeder vessel (moving ahead) experienced significant stern down trim and sinkage in addition to increased resistance, as expected.

The introduction of vents to the well dock cause the following: a reduction in the bow down trim, the reappearance of a slight bodily sinkage and a significant reduction in longitudinal force for the docking manoeuvre. For the departure manoeuvre the introduction of vents reduced the stern down trim, the bodily sinkage and the longitudinal force, confirming that there are distinct benefits to including vents during docking and departure operations. Testing of intermediate vent sizes indicated that a large amount of the benefits can be obtained by simply introducing a vent of a relatively small size and that increasing the vent size (in terms of cross-sectional area) by a factor of four fails to yield a similar increase in effectiveness.

The counterintuitive confined water behaviour during docking suggested that there were interesting hydrodynamic phenomena occurring within the well dock that warranted further investigation. A third experimental program was undertaken where PIV techniques were adopted to visualise the flow field within the closed end of the well dock and through the vent openings. The inability of the water to flow past the sides and under the bottom of the feeder vessel fast enough to maintain equilibrium caused a rise in free surface elevation at the closed end of the well dock. This contributed to the counter intuitive behaviour observed during the previous experiments. The opposite effect was seen during the departure manoeuvre with the water not being able to flow fast enough past the feeder vessel to the closed end of the well dock, thus causing a depression in free surface elevation which accentuates the expected confined water effects. This region of near zero flow was reduced with increasing vent size as water was able to flow in and out of the side vents directly adjacent to this region. As the vent size decreased, the flow velocity through the vent increased and more flow was found to be moving through the main entrance of the well dock.

Ultimately, vents are likely to be required within the well dock of the FHT concept to reduce the confined water effects during docking and departure manoeuvres. This will reduce unusual handling characteristics and make the operations easier for the master and thus improve safety. The combined opening size of these vents does not need to be any larger than the cross sectional area of the feeder vessel to leverage the majority of the benefit. By minimising the vent size it is possible to control the adverse effect of the vents on the docked seakeeping performance but caution should be exercised to avoid a vent configuration that produces hazardous environments within the well dock when the feeder vessel is not docked.

5.2 Further Work

While the hydrodynamics of a feeder vessel operating in a confined well dock are now better understood as a direct result of this initial study into the concept, there is plenty of scope to expand the study to develop further knowledge. This would ideally expand the experimental scope of investigation to cover extra vent sizes, well dock and vent geometries, sea states, propulsor effects as well as quantifying the wave environment and boundary layers within the well dock. Priority should be given to investigations focusing on vent sizes of 25% and smaller as well as understanding the effects of irregular sea states and wave headings other than head seas. A number of aspects for further investigation are ideally suited to experimental investigation but certain aspects could also be addressed using numerical methods. The findings of this study can be used to inform future numerical simulation with the data presented being used for validation purposes. The numerical simulations attempted during this study identified a number of modelling challenges related to the complicated geometric features and the close proximity between vessels.

It would desirable to investigate a greater number of vent sizes to increase the resolution between the no vents and the vents 50% open condition. Vents that represent a total opening up to an area equal to the immersed cross sectional plan area of the feeder vessel should be the focus for further investigation as larger vents have been shown to be unnecessary and contribute to unfavourable seakeeping behaviour. It is expected that the smaller vent sizes can be made even more effective by exploring the impact of well dock and vent geometry. Smoother flow throughout the well dock and vents was demonstrated to be beneficial under the operational conditions tested. It is hypothesised that by optimising the geometry of the well dock and in particular the entry to the vents, the same docking benefits could be obtained with smaller vents leading to a better balance between the docking and docked operational conditions. In addition to modifying the geometry, future investigation could be performed on the effect of clearance between the feeder vessel and the well dock. If the under keel or lateral clearance were to be continually increased, there would come a point where the requirement for well dock vents would be removed all together. This removal of the requirement for well dock vents would likely come at significant expense due to the increased size of mothership.

Further testing to increase the scope of investigation beyond the current restricted range of wave environments could deepen the understanding of well dock operations in an open seaway. The tested conditions have to this point been restricted to regular head seas for the seakeeping tests and calm water for the docking manoeuvre because the concept was previously untested and posed significant risk to equipment highlighting that a foundation understanding was required before delving deeper. Further work could investigate the seakeeping performance in more realistic, irregular wave spectra and a wider range of wave headings. A logical successor to the docking performance body of work would be to introduce a seastate and allow the mothership to heave and pitch now that it has been shown that longitudinal feeder vessel motion in isolation does not cause contact between the vessels.

The boundary layers of both the bottom of the well dock and the feeder vessel were hypothesised to be influencing the flow between the feeder vessel and the well dock bottom. Further investigation of the boundary layer formation and thickness over these surfaces during docking and departure operations could provide useful knowledge for optimising the clearance between the vessels and the vent opening sizes. Another aspect that will certainly influence the flow within the well dock during docking and departure is the propulsors. The effect of the flow on the propulsors was discussed but the effect of the propulsors on the flow was not considered during the present investigation. This is a region that is important to understand if the feeder vessel is to dock and depart under its own power.

A preliminary attempt was made to investigate the wave environment within the well dock but the limitations of this data were discussed along with the advantage of more targeted data. Further experimental investigation could yield a measure of the wave environment within the well dock and allow the identification of the conditions under which the feeder vessel is able to safely enter the well dock. This operational envelope can then be used to further inform the feasibility study for a proposed implementation location. It may also be worth investigating ways to reduce the wave environment within the well dock, for example through the use of a less reflective end wall (the present study only considered a bluff vertical wall). Also of potential interest is the additional sheltering effect that may result while an OGV is moored alongside the mothership (the present study only considers the case when there is no OGV alongside).

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APPENDIX

Uncertainty Analysis

Applied uncertainty approach

The uncertainty within the experimental measurements has been assessed using the approach prescribed by the ITTC for experimental hydrodynamics (ITTC, 2014). When determining the uncertainty of the results presented the significant sources of error were identified and quantified as demonstrated in Table A.1. These individual uncertainties were then combined to find the combined standard uncertainty using the law of propagation of uncertainty using the data reduction equations outlined within this appendix in the manner prescribed by the ITTC recommended procedures and guidelines.

Uncertainties smaller than one fifth of the largest uncertainties were deemed to be negligible as proposed by Longo and Stern (2005).

Table A.1: Typical uncertainty values within the measurement systems used.

Source of uncertainty	**Typical uncertainty value**
Uncertainty within Qualisys heave measurements	2 mm in 200 mm
Uncertainty within Qualisys pitch measurements	1 degrees in 25 degrees
Voltage measurement for wave probe	30 mV in 17 V
Calibration factor for wave probe	0.03 mm/V in 5.8 mm/V
Calibration factor for forward LVDT	0.02 mm/V in 5.1 mm/V
Calibration factor for aft LVDT	0.01 mm/V in 5.2 mm/V
Voltage measurement for speed	25 mV in 1.8 V

Calibration of raw voltage measurements

All wave probe, LVDT and load cell measurements were obtained by measuring the raw voltage produced by the instrument which was calibrated during post processing using a calibration factor obtained by applying known loads or displacements to the instruments. The calibration of the raw voltages was performed according to Equation A.1 which uses the example of longitudinal force measurement.

$$F_x = V_{Fx} \times C_{Fx} \tag{A.1}$$

Where;

F_{Fx} = Longitudinal force on feeder vessel
V_{Fx} = Load cell voltage output
C_{Fx} = Load cell calibration factor

Evaluation of combined uncertainty

The combined uncertainty for each reported parameter was evaluated as prescribed within the ITTC guidelines for expressing uncertainty in experimental hydrodynamics. The way that the law of propagation of uncertainty was applied is demonstrated for the pitch response of the FHT in a sea state is presented as Equation A.2.

$$u_{z_{ND-FHT}}{}^{2} = \left(\frac{\partial z_{ND-FHT}}{\partial z_{FHT}} u_{z_{FHT}}\right)^2 + \left(\frac{\partial z_{ND-FHT}}{\partial V_{WP}} u_{V_{WP}}\right)^2 + \left(\frac{\partial z_{ND-FHT}}{\partial C_{WP}} u_{C_{WP}}\right)^2 \qquad \text{(A.2)}$$

Where the partial derivatives can be obtained from the data reduction equation;

$$z_{ND} = \frac{z}{V_{WP} \times C_{WP}}$$

And therefore;

$$\frac{\partial z_{ND-FHT}}{\partial z_{FHT}} = \frac{1}{V_{WP} C_{WP}}$$

$$\frac{\partial z_{ND-FHT}}{\partial V_{WP}} = \frac{z_{FHT}}{C_{WP}}$$

$$\frac{\partial z_{ND-FHT}}{\partial C_{WP}} = \frac{z_{FHT}}{V_{WP}}$$

Where;

$u_{z_{ND-FHT}}$ = Uncertainty within the non-dimensional FHT heave

z_{ND-FHT} = Non-dimensional FHT heave

$u_{z_{FHT}}$ = Uncertainty within the FHT heave measured by Qualisys

z_{FHT} = FHT heave measured by Qualisys

$u_{V_{WP}}$ = Uncertainty within the voltage measurement of the wave probe

V_{WP} = Voltage measurement of the wave probe

$u_{C_{WP}}$ = Uncertainty within the wave probe calibration factor

C_{WP} = Wave probe calibration factor

Pitch and heave motion response

The pitch and heave response of the vessel were directly measured using non-contact infrared cameras (Qualisys motion measurement system). The heave and pitch measurements were then non-dimensionalised using Equations A.3 and A.4 respectively.

$$z_{ND} = \frac{z}{\zeta_A} \tag{A.3}$$

$$\theta_{ND} = \frac{\theta}{k \times \zeta_A} \tag{A.3}$$

Where;

z_{ND} = *Non-dimensional Heave*
z = *Heave Amplitude*
θ_{ND} = *Non-dimensional Pitch*
θ = *Pitch Amplitude*
ξ_A = *Wave Amplitude*
k = *Wave Number* $= \frac{2\pi}{L_W}$
L_W = *Wavelength*

For the purpose of estimating the uncertainty within the heave and pitch measurements, three sources of error were considered; Qualisys measurement of pitch and heave, voltage measurement of wave probe and calibration factor for wave probes. Uncertainty within the model geometry and gravitational acceleration were ignored as they were smaller than one fifth of the maximum uncertainty source.

Feeder vessel sinkage and trim

The feeder vessel sinkage and trim during docking operations was measured using two LVDTs mounted on the fore and aft tow posts. The measurements from the two LVDTs were combined to determine the sinkage and trim of the feeder vessel using Equation A.5 and A.6 respectively. The heave and sinkage results were then non-dimensionalised with respect to the static under keel clearance as outlined in Equations A.7 and A.8.

$$z_{LCB} = z_{fwd} - \frac{(z_{fwd} - z_{aft}) \times \Delta x_{fwd\ post\ to\ LCB}}{\Delta x_{between\ posts}} \tag{A.5}$$

$$t = \frac{\left(z_{fwd} - z_{aft}\right) \times L}{\Delta x_{between\ posts}} \tag{A.6}$$

$$z_{ND-LCB} = \frac{z_{LCB}}{UKC_s} \tag{A.7}$$

$$t_{ND} = \frac{t}{2 \times UKC_s} \tag{A.8}$$

Where;

z_{LCB}	= Sinkage at LCB
$z_{\text{ND-LCB}}$	= Non-dimensional sinkage at LCB
z_{fwd}	= Sinkage at the forward post
z_{aft}	= Sinkage at the aft post
$\Delta x_{fwd\ post\ to\ LCB}$	= Longitudinal distance between the forward post and the LCB
$\Delta x_{between\ \text{posts}}$	= Longitudinal distance between the posts
t	= Trim between perpendiculars
t_{ND}	= Non-dimensional trim betweeen perpendiculars
L	= Length between perpendiculars
UKC_s	= Static under keel clearance

After neglecting sources of uncertainty smaller than one fifth of the largest source there were four sources considered when estimating the uncertainty of the sinkage and trim of the feeder vessel; forward LVDT calibration factor, aft LVDT calibration factor, the calibration factor for the wave probe and the uncertainty in measuring the static under keel clearance. Some of the negligible sources of uncertainty within the sinkage and trim measurement are the gravitational acceleration, calibration apparatus, model geometry, forward LVDT voltage measurement, aft LVDT voltage measurement, voltage measurement for the wave probe, water temperature and density.

Longitudinal force

The longitudinal force on the feeder vessel was monitored using two load cells, one on each of the two tow posts. The aft load cell is mounted to the model via a slider and was included to ensure that there was no excessive friction within the coupling. The longitudinal force at the forward post is non-dimensionalised according to Equation A.9.

$$\mathrm{F}_{ND-x} = \frac{F_x}{\frac{1}{2} \times \rho \times v^2 \times L^2} \tag{A.9}$$

Where;

F_x = Longitudinal force on feeder vessel
F_{ND-x} = Non-dimensional longitudinal force on feeder vessel
ρ = Water density
v = Vessel speed
L = Length between perpendiculars

As there was negligible friction within the aft slider the uncertainty within longitudinal force on the model is able to be determined using only the forward load cell. The uncertainty within the voltage measurement of speed was more than eight times greater than the next largest source of uncertainty therefore this is the only source that was considered for the longitudinal load. Some of the negligible sources of uncertainty within the longitudinal force measurement are the load cell voltage measurement, load cell calibration factor, gravitational acceleration, calibration masses, water temperature and density and calibration factor for speed.